Cranfield
UNIVERSITY

Wheels and Tracks Study

(10 - 25 Ton Armoured Fighting Vehicles)

RERUM COGNOSCERE CAUSAS

Report No. RMCS/ESD/PCB/266/00
March 2000

N68171-00-M-5554

R&D 8956-MS-01

Engineering Systems Department
Royal Military College of Science
Shrivenham
Swindon SN6 8LA
UK

ZGS104R

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20001024 160

Wheels and Tracks Study

(10 - 25 Ton Armoured Fighting Vehicles)

Authors:
P C Barton
M D Bennett
L C Hall
J G Hetherington

Report No. RMCS/ESD/PCB/266/00
March 2000

Engineering Systems Department
Royal Military College of Science
Shrivenham
Swindon SN6 8LA

ZGS104R

SUMMARY

This study was conducted by the Engineering Systems Department of Cranfield University, at the Royal Military College of Science, Shrivenham, UK, for the the Department of the Army, United States Army Research Laboratory, Aberdeen Proving Ground, Maryland, USA. The scope of the study covers Terrain Accessibility (Section 1), Suspension and Automotive Performance (Section 2) and Other Factors (Section 3) in connection with tracked and wheeled armoured fighting vehicles (AFVs) in the 10 to 25 US ton range.

Two aspects of terrain accessibility were covered in detail - soft-soil trafficability and obstacle crossing. Several different predictive methods were used to compare the trafficability of a sample of sixteen AFVs in the 10 to 25 US ton range, for clay soils and sands. The sample comprised eight tracked vehicles and eight wheeled vehicles, four of which were equipped with a central tyre inflation system (CTIS). There were considerable differences in the predictions derived from the various methods, but some clear trends emerged. Overall, tracked AFVs were found to exhibit superior trafficability on both types of soil. The wheeled vehicles equipped with CTIS were better than those without, and in some cases could approach the capability of a tracked vehicle.

The ability of wheeled and tracked AFVs to cross undeformable trenches and to climb rigid steps was examined both theoretically and by means of a survey of current vehicles. It was found that tracked AFVs, on a size for size basis, are better able to overcome these types of obstacle than their wheeled counterparts.

The influence of suspension and transmission systems on the automotive performance of AFVs was investigated using computer models. The performance of typical wheeled and tracked AFV suspension systems, fitted to a 20 US ton AFV, were compared when the vehicle is driven over a ramp, over a sinusoidal track and over random terrain. It was found that both types of vehicle offered broadly similar ride quality, though there were some differences in detail. Suspensions employing a hardening spring characteristic and ample suspension travel were found to provide a better ride.

Another computer program was used to model three types of transmission system, with the same engine, installed in a typical AFV. The effects on accelerative performance on level ground and speed on a 30 degree gradient were investigated. Two of the transmissions were based on stepped-ratio gearboxes, one manual change with a dry-plate clutch, the other automatic with a torque converter. The third transmission provided continuously variable ratios. It was concluded that the continuously variable transmission gave superior results.

A variety of other factors which could influence the choice between wheeled and tracked AFVs in the 10 to 25 US ton range were explored. These included packaging, strategic and operational mobility, survivability, cost, supportability and others. The advantages and disadvantages of wheeled and tracked AFVs are discussed and tabulated for each of these factors.

CONTENTS

INTRODUCTION

This report was undertaken in response to a request from the Department of the Army, United States Army Research Laboratory, Aberdeen Proving Ground, Maryland, USA.

The scope of work as set out in Annex 1 of **Fixed Price Quotation for Wheels and Tracks Study - 20 Tonne Vehicle,** dated 7 December 1999 is reproduced below:

Scope of Wheels and Tracks Study

1) TERRAIN ACCESSIBILITY	
Mobility on soft soils (sand and clay) (including the effect of CTIS)	Detailed quantitative analysis (similar in scope to Report No. RMCS/ESD/LCH/175/99)
Gap crossing	AFV survey plus analysis
Step climbing	AFV survey plus analysis
Urban obstacle negotiation - negotiation of rubble - negotiation of dwarf walls	 Brief commentary AFV survey plus analysis
Effect of suspension type on mobility	Qualitative commentary
Advanced track and wheel designs	Brief commentary
2) AUTOMOTIVE PERFORMANCE	
Acceleration, Sustained velocity for various terrains; - influence of suspension type - influence of suspension performance - influence of transmission type	 Brief commentary Detailed quantitative analysis Detailed quantitative analysis
Fuel consumption	Brief commentary
3) OTHER FACTORS	
Capacity Mobility (strategic/operational) Survivability Firepower Cost Supportability Human Factors Political Factors	Qualitative commentary (similar in scope to Report No. RMCS/ESD/PCB/174/99)

The report is thus compiled in four distinct sections:

1) TERRAIN ACCESSIBILITY

2) AUTOMOTIVE PERFORMANCE

3) OTHER FACTORS

4) MAIN CONCLUSIONS

In this study it is assumed that a Future Combat System able to meet the required level of survivability will, of necessity, need some level of armour protection. It is further assumed that it will be based on a land vehicle which will be referred to throughout as an Armoured Fighting Vehicle (AFV).

1 TERRAIN ACCESSIBILITY

Terrain accessibility is a vital characteristic of an effective Armoured Fighting Vehicle (AFV). The whole raison d'etre of such vehicles is to give military commanders the capability, as far as possible, of projecting force to any point within the theatre of operations. Due to the varied nature and location of military conflicts AFVs should therefore ideally be able to operate over any type of terrain. In practice there are limitations but these should be as unrestrictive as possible.

There are several factors which may limit the mobility of an AFV. Since AFVs are land vehicles their weight must be supported by the terrain on which they operate. If that terrain is very soft, the ground may not be capable of doing this without excessive sinkage, which can lead to immobility. This aspect is dealt with in Section 1.1 below.

Another source of immobility is obstacles, which appear in a variety of forms. These may be steep ramps or steps in the terrain, either man-made or artificial. They may take the form of ditches or trenches into which the vehicle may fall and be unable to extricate itself. Alternatively they may be urban rubble or obstructions of a similar nature. These are discussed in Section 1.2. Another mobility problem is presented by water obstacles, which may be shallow enough to ford, or deep enough to require schnorkelling or an amphibious capability. This type of obstacle is beyond the scope of this study.

Terrain accessibility is also influenced by suspension design which can affect the ground pressure when the vehicle operates on rough terrain and the ability of the vehicle to negotiate obstacles. The detailed design of wheels and tracks will also have a bearing on the terrain accessibility. These matters are addressed in Sections 1.3 and 1.4.

1.1 TRAFFICABILITY ON SOFT SOILS

Approach Adopted

This aspect of the study was based on the work reported in [1.1], which included the identification of the various methods in use for predicting and comparing the mobility of wheeled and tracked vehicles when operating on soft soil. These methods were categorised and the most appropriate were selected for detailed examination. The results of this previous research are presented in Annexes 1A and 1B to this section of the report. Annex 1B lists the methods selected and gives some information regarding their origins. For this earlier study, two computer programs were produced to evaluate the mobility predictions from each method, one for clay soils and the other for sand.

A survey of armoured fighting vehicles in the range 10 to 25 US tons was then carried out and sixteen of these were selected for examination. Eight were tracked and eight wheeled, including four fitted with central tyre inflation systems.

Using Janes [1.2] and other sources a data file was constructed for each chosen vehicle for use in conjunction with the programs. The predictions from the various methods were then tabulated and the vehicles ranked in order of their predicted soft soil mobility according to each method.

Definition of "Soft Soil Trafficability"

For the purposes of this study "soft soil trafficability" is defined as the ability of a vehicle to develop drawbar pull when operating on soft terrain, assuming that at all times there is sufficient torque available from the drive train to rotate the roadwheels or sprockets. Therefore it is essentially confined to the terramechanics of the situation which is concerned with the methods available for predicting the capability of a vehicle to operate on soft soil. As such it does not

address the wider aspects of mobility such as manoeuvrability or obstacle crossing, which are covered in a later section of the report.

1.1.1 Description of Computer Programs

By adapting and extending the programs described in [1.1], two new computer programs were produced to calculate a range of trafficability characteristics and predictions for off-road vehicles. Program USMOBW is for wheeled vehicles and USMOBT for tracked vehicles, each covering clay, sandy soils and muskeg. The algorithms were based on the equations given in Annex 1C. For simplicity it was assumed that the vehicle weight is equally distributed between the wheelstations and that, in the case of wheeled vehicles, all wheels are driven via a transmission system fitted with an effective traction control system. These are reasonable assumptions for well designed AFVs loaded to combat weight. It should be noted that the uncertainty of terramechanics predictions is such that any additional errors introduced as a consequence of these assumptions are unlikely to be highly significant.

The programs include predictions based on the mobility numerics method for both clays and sands. In the case of clay soils, the programs calculate the drawbar pull for a range of cone index values and identify that at which the resistance to motion on level ground just exceeds the gross traction, i.e. when the drawbar pull is zero and the vehicle becomes immobilised. This approach was found not to work satisfactorily for sands, probably because the equations were operating outside the range of data on which they were based. Therefore the programs were designed to reveal the gradient at which the gross traction just equals the total resistance to motion, i.e. when the vehicle becomes immobilised. The analysis was performed for a very soft sand and repeated for a firm sand (penetration resistance gradients of 1750 and 6500 kPa/m respectively). Only a small number of empirical relationships for sand were found in the literature of which two were chosen for tracked AFVs and three for wheeled, including those used in the latest version of the NATO Reference Mobility Model (NRMM II.)

The programs were used to derive the predicted mobility characteristics of a selection of typical armoured fighting vehicles in the weight range of interest.

1.1.2 Selection of Representative Vehicles

Data was obtained for sixteen AFVs in the 10-25 US ton range and for each a datafile was constructed using mainly Janes [1.2] backed up by other sources. Eight of these vehicles are tracked, including armoured personnel carriers, reconnaissance vehicles, light tanks and a self propelled gun. The other eight are wheeled AFVs including armoured personnel carriers and reconnaissance vehicles. The tracked vehicles include those having 5, 6 and 7 wheelstations per side and the wheeled vehicles include 4x4, 6x6 and 8x8 configurations. Four of the wheeled vehicles are equipped with a Central Tyre Inflation System (CTIS).

It proved impracticable to cover the whole weight range for both wheeled and tracked AFVs. The lightest suitable tracked vehicle found in this range was M113-A1 at 12.2 US tons (11.07 tonne). Strictly speaking the CV9040 should have been excluded since it is marginally heavier than 25 US tons, but it was felt worth including since it is a tracked AFV which has been designed with particular emphasis on low ground pressure. For wheeled AFVs the lightest suitable candidate was Grizzly at 11.76 US tons (10.5 tonne) and the heaviest was Fuchs at 20.94 US tons (19 tonne). Not surprisingly, there was a wider choice of wheeled vehicles in this weight range, and their combat weights tended to be lower than those using tracks. However, no suitable wheeled AFVs were found in the range 10 to 11.5 US tons.

Details of the AFVs selected for the trafficability study and the data used in running the programs are shown in Annex 1D. Note that, for the four vehicles equipped with CTIS, the tyre deflections

used are those likely at the lowest (emergency) tyre inflation pressures, which would correspond with a maximum recommended speed of 20 km/h or less. This was chosen to present the highest mobility levels which these vehicles are capable of offering. In practice it would not be advisable to operate at these low pressures over large distances.

1.1.3 Predictions for Clays

The mobility predictions for the twelve vehicles when operating on fine-grained (clay) soils are summarised in Table 1-1 and plotted on graphs 1E1 to 1E10 (see Annex 1E). The first eight vehicles in Table 1-1 are tracked, and listed in ascending order of weight. The next four are wheeled vehicles fitted with CTIS and the last four are wheeled vehicles without CTIS, also in ascending weight order. The first five columns of predictions (a to e) are *mobility characteristic parameters* and the next three (f to h) are *mobility limit parameters* (see Annex 1B.1). The final columns (i and j) are derived from mobility numerics analysis. The predictions in columns f to j should, theoretically, be the same.

In Table 1-2 the vehicles have been placed in rank order according to the method of prediction. If all methods were "correct" then the rank order for each method would be identical. Note that the values of Limiting CI in column f are found by multiplying the Rowland MMP (column d) values by a constant, and hence will generate the same rank order. Therefore the rank order in column d has not been duplicated in column f. In column b the NGP values for tracked vehicles have been ranked with the APSG values for wheeled vehicles. In column j the WES values for tracks have been ranked with the R&H values for wheels. In all columns the tracked vehicles are shown in **bold** typeface. (Refer to Annexes 1B and 1C for details of the terms NGP, APSG, MI, MMP, Limiting CI, VCI, VLCI, Min CI (WES, R&H))

Vehicle	Wheels	Mass	a NGP	b APSG	c Mobility Index	d MMP (Rowland)	e MMP (Maclaurin)	f Limiting CI	g VCI	h VLCI	i Min CI (R & H)	j Min CI (WES)
		tonne	kPa	kPa		kPa	kPa	kPa	kPa	kPa	kPa	kPa
M113-A1	10	11.07	53	(53)	53	126	126	105	116	164	139	(139)
Stormer	10	12.7	49	(49)	45	141	141	117	105	182	150	(150)
AMX-10P	10	14.5	57	(57)	51	165	165	137	114	213	180	(180)
SK105-A1	10	17.7	75	(75)	76	215	215	178	150	278	232	(232)
BMP-3	12	18.7	59	(59)	60	186	186	154	127	240	198	(198)
M108	14	22.45	73	(73)	73	181	181	150	145	234	195	(195)
Stingray II	12	22.6	80	(80)	80	212	212	176	156	274	229	(229)
CV9040	14	22.8	53	(53)	45	134	134	112	105	174	146	(146)
Pandur	6 (CTIS)	13.5	126	88	112	330	214	274	191	255	342	301
BTR-80	8 (CTIS)	13.6	90	62	76	244	140	203	150	169	243	216
Panther	4 (CTIS)	14	117	81	116	285	179	236	195	218	317	281
AMX-10RC	6 (CTIS)	15.88	113	78	101	290	174	241	179	210	300	268
Grizzly	6	10.5	122	96	110	492	297	409	238	326	511	450
Saxon	4	11.66	125	100	114	412	265	342	229	300	457	404
LAV-25	8	12.79	111	87	99	473	271	393	221	298	468	413
Fuchs	6	19	135	108	131	479	288	397	242	326	497	439

Table 1-1 Trafficability Predictions for Clay

Rank Order	a NGP	b APSG	c Mobility Index	d MMP (Rowland)	e MMP (Maclaurin)	f Limiting CI	g VCI	h VLCI	i Min CI (R & H)	j Min CI (WES)
1	**Stormer**	**Stormer**	**Stormer**	**M113-A1**	**M113-A1**		**CV9040**	**M113-A1**	**M113-A1**	**M113-A1**
2	**CV9040**	**CV9040**	**CV9040**	**CV9040**	**CV9040**		**Stormer**	BTR-80	**CV9040**	**CV9040**
3	**M113-A1**	**M113-A1**	**AMX-10P**	**Stormer**	BTR-80		**AMX-10P**	**CV9040**	**Stormer**	**Stormer**
4	**AMX-10P**	**AMX-10P**	**M113-A1**	**AMX-10P**	**Stormer**		**M113-A1**	**Stormer**	**AMX-10P**	**AMX-10P**
5	**BMP-3**	**BMP-3**	**BMP-3**	**M108**	**AMX-10P**	See	**BMP-3**	AMX-10RC	**M108**	**M108**
6	**M108**	BTR-80	**M108**	**BMP-3**	**M108**		**M108**	**AMX-10P**	**BMP-3**	**BMP-3**
7	**SK105-A1**	**M108**	**SK105-A1**	**Stingray II**	**BMP-3**		**SK105-A1**	Panther	**Stingray II**	BTR-80
8	**Stingray II**	**SK105-A1**	BTR-80	**SK105-A1**	**Stingray II**		BTR-80	**M108**	**SK105-A1**	**Stingray II**
9	BTR80	**Stingray II**	**Stingray II**	BTR-80	**SK105-A1**	MMP	**Stingray II**	**BMP-3**	BTR-80	**SK105-A1**
10	LAV-25	AMX-10RC	LAV-25	Panther	AMX-10RC		AMX-10RC	Pandur	AMX-10RC	AMX-10RC
11	AMX-10RC	Panther	AMX-10RC	AMX-10RC	Panther		Pandur	**Stingray II**	Panther	Panther
12	Panther	LAV-25	Grizzly	Pandur	Pandur		Panther	**SK105-A1**	Pandur	Pandur
13	Grizzly	Pandur	Pandur	Saxon	Saxon	(Rowland)	LAV-25	LAV-25	Saxon	Saxon
14	Saxon	Grizzly	Saxon	LAV-25	LAV-25		Saxon	Saxon	LAV-25	LAV-25
15	Pandur	Saxon	Panther	Fuchs	Fuchs		Grizzly	Grizzly	Fuchs	Fuchs
16	Fuchs	Fuchs	Fuchs	Grizzly	Grizzly		Fuchs	Fuchs	Grizzly	Grizzly

Tracked AFVs shown in **bold** type

Table 1-2 Predicted AFV Rank Orders for Clays

1.1.4 Predictions for Sands

The mobility predictions for sands have been presented in a similar fashion in Table 1-3 and plotted on graphs 1E11 to 1E16 in Annex 1E. The results have been put in separate columns since they are derived from different empirical relationships.

Vehicle	a	b	c	d	e	f	g	h
	G = 1750 kPa/m				G = 6500 kPa/m			
	Gradient (Turnage) deg	Gradient (R&H) deg	Gradient (WES) deg	Gradient (NRMM)) deg	Gradient (Turnage) deg	Gradient (R&H) deg	Gradient (WES) deg	Gradient (NRMM) deg
M113-A1	27.3			29.1	33.8			33.7
Stormer	28.3			29.8	34.9			33.9
AMX-10P	27.5			29.2	34			33.8
SK105-A1	26			28.2	32.4			33.4
BMP-3	27.8			29.3	34.3			33.8
M108	26.8			28.8	33.2			33.6
Stingray II	26.2			28.3	32.5			33.4
CV9040	29.2			30.4	35.8			34.2
Pandur		10	1.2	1.9		26.1	13.2	15.2
BTR-80		16.2	4.1	5.4		29.1	16.8	18.8
Panther		15.9	3.9	5.1		28.9	16.6	18.5
AMX-10RC		14.5	3.1	4.2		28.2	15.7	17.6
Grizzly		0	0	0		15.7	3.8	4.8
Saxon		0	0	0		21.6	8.3	8.7
LAV-25		0	0	0		17	4.6	5.8
Fuchs		0	0	0		20.8	7.5	7.9
				RANK ORDER				
1	**CV9040**			**CV9040**	**CV9040**			**CV9040**
2	**Stormer**			**Stormer**	**Stormer**			**Stormer**
3	**BMP-3**			**BMP-3**	**BMP-3**			**BMP-3**
4	**AMX-10P**			**AMX-10P**	**AMX-10P**			**AMX-10P**
5	**M113-A1**			**M113-A1**	**M113-A1**			**M113-A1**
6	**M108**			**M108**	**M108**			**M108**
7	**Stingray II**			**Stingray II**	**Stingray II**			**Stingray II**
8	**SK105-A1**			**SK105-A1**	**SK105-A1**			**SK105-A1**
9		BTR-80	BTR-80	BTR-80		BTR-80	BTR-80	BTR-80
10		Panther	Panther	Panther		Panther	Panther	Panther
11		AMX10RC	AMX10RC	AMX10RC		AMX10RC	AMX10RC	AMX10RC
12		Pandur	Pandur	Pandur		Pandur	Pandur	Pandur
13						Saxon	Saxon	Saxon
14						Fuchs	Fuchs	Fuchs
15						LAV-25	LAV-25	LAV-25
16						Grizzly	Grizzly	Grizzly

Tracked AFVs shown in **bold** type

Table 1-3 Trafficabilty Predictions for Sands

1.1.5 Predictions for Muskeg

Vehicle cone index values for muskeg were predicted for the sixteen vehicles chosen for the study. For the tracked vehicles they lay in the range 133 to 158 kPa. The wheeled vehicles produced much higher values, lying in the range 332 to 496 kPa. It should be noted that the equations used in computer model USMOBW, which are those employed in NRMM II, give no credit for vehicles fitted with CTIS.

1.1.6 Discussion

1.1.6.1 Trafficability on Clays

Mobility Characteristic Parameters

An examination of Table 1-1 shows that NGP gives tracked vehicles a clear advantage over wheeled vehicles and, in general, that their trafficability decreases with vehicle weight, (see graph 1E1, Annex 1E). The exception to this trend is CV9040, which has been designed with operation on snow very much in mind and has an exceptionally low ground pressure for a vehicle of its weight. For wheeled AFVs there is not such a clear trend. Note that the NGP approach gives no credit for CTIS and the benefits of low tyre pressures are therefore not recognised. However if the French APSG method, which assumes a larger area of contact with the ground and allows for CTIS, is used for wheeled vehicles, the gap between the capability of the better wheeled vehicles and the tracked vehicles appears to narrow considerably.

The American MI parameter gives a broadly similar rank order for tracked vehicles to that of the NGP and like APSG/NGP shows an overlap between wheeled and tracked vehicles, but to a reduced extent. However it gives a very different forecast for the 4x4 Panther than the other parameters in this group. Like NGP, Mobility Index does not recognise the benefits of low tyre pressures and, for tracked AFVs, predicts a decrease in trafficability with vehicle weight (see graph 1E3 Annex 1E).
Similarly to NGP, the Rowland MMP polarises tracked and wheeled vehicles, which is not surprising since the formula for wheels was arrived at indirectly and, fundamentally, does not predict the same thing (see Annex 1B). Note that this formula recognises the benefits of CTIS, ranking all the vehicles so equipped above those without this system.

The Maclaurin MMP, which is used in the Statement of Requirement for Multi-Role Armoured Vehicle (MRAV), is more favourable to wheeled AFVs and is particularly kind to BTR-80, which is predicted to out perform all but the best tracked AFVs. Again wheeled AFVs with CTIS score relatively highly according to this parameter.

Mobility Limit Parameters

Since limiting cone index is proportional to the Rowland MMP the Limiting Cone Index ranking of the vehicles is the same. Tracked vehicles exhibit the highest mobility followed by wheeled vehicles with CTIS and then by those without.

VCI is derived from MI but the formula for wheels includes a term which gives credit for CTIS. This might be expected to give a similar result to that from the Rowland MMP. Although both give tracks an advantage, with a recognition of the benefit of CTIS in wheeled vehicles, there are some surprising differences. In particular M113 comes out relatively badly when compared with the predictions of the other parameters in this category and BTR-80 is clearly placed in the tracked vehicle league.

The recently proposed Vehicle Limiting Cone Index (VLCI) [1.3] is the best disposed to wheeled

vehicles with a large overlap of the wheeled and tracked vehicle predictions. It suggests that a modern wheeled vehicle, with CTIS at emergency tyre pressures, can be quite comparable with tracked vehicles. This appears to be too good to be true and this parameter certainly needs further verification. As has been pointed out in Annex 1B (see 1B.1.3.3 and 1B.1.4.3), it is based upon very good experimental technique but using a comparatively lightly loaded track system and single wheels. There must be some concern over the validity of the extrapolation, particularly for the heavier vehicles.

Predictions from Empirical Methods

The minimum cone index predicted by mobility numerics gives almost the same rank order as the Rowland MMP parameter. In the case of wheeled vehicles this is perhaps not too surprising, since MMP_W was derived using mobility numerics. The alternative WES equation for wheeled vehicles gives the same rank order but predicts a higher level of mobility for wheels which overlaps that of the tracked vehicles.

Analysis of Minimum Cone Index Predictions

Essentially the three mobility limit parameters and the mobility numerics based minimum cone index all claim to predict the value of cone index which will just immobilise the vehicle. However, an inspection of columns f to i in Table 1-1 reveals that they all give widely differing estimates. It is instructive to examine the mean values of the minimum soil strength predictions tabulated in columns f to i in Table 1-1. These have been calculated for each mobility parameter for the samples of tracked vehicles, wheeled vehicles with CTIS and wheeled vehicles without CTIS which were chosen for this study. The results are summarised in Table 1-4.

For tracked vehicles the most optimistic forecast is given by VCI followed by limiting cone index, mobility numerics and VLCI. For wheeled vehicles the order is VCI followed by VLCI, limiting cone index and mobility numerics. The spread of values is large, with the ratio of worst to best estimates ranging from about 1.5 to 2. Clearly these methods are not very consistent and it is not obvious which is the most accurate for vehicles in this weight range.

Parameter	based on	Minimum Soil Cone Index (kPa)		
		Tracks	**Wheels+CTIS**	**Wheels-CTIS**
CI_L	MMP (Rowland)	141	239	385
VCI	Mobility Index	127	179	233
VLCI	Maclaurin expts	220	213	313
Min CI	Mobility numerics	184	301	483

Table 1-4 Average Trafficability Predictions

It is clear that all the systems, with the exception of VLCI, indicate that the tracked vehicles offer the best trafficability on average, followed by wheeled vehicles with CTIS and then wheeled vehicles with tyres inflated to road pressures. However, the VLCI parameter suggests that wheeled vehicles with tyres at emergency inflation pressures can out-perform tracked vehicles.

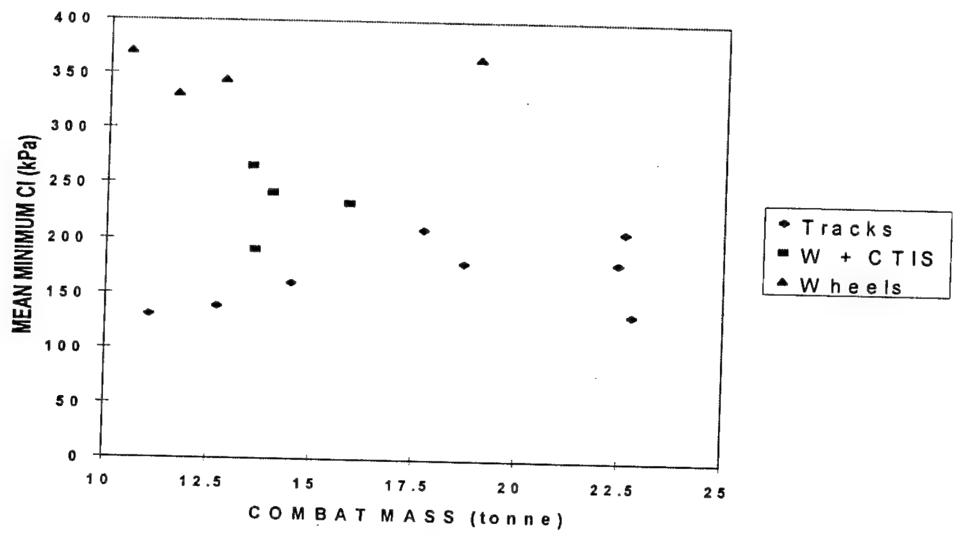


Figure 1-1 Mean Trafficability Predictions

Another way of using this data is to determine, for each vehicle, the average prediction of the four parameters tabulated in columns f to i in Table 1-1. This has been calculated and presented in Table 1-5 and in Figure 1-1.

Rank Order	Vehicle	Tracked/Wheeled	Mass (tonne)	Mean Minimum Cone Index (kPa)
1	**M113-A1**	T	11.07	131
2	**CV9040**	T	22.8	134
3	**Stormer**	T	12.7	139
4	**AMX-10P**	T	14.5	161
5	**BMP-3**	T	18.7	180
6	**M108**	T	22.45	181
7	BTR-80	W+CTIS	13.6	191
8	**Stingray II**	T	22.6	209
9	**SK105-A1**	T	17.7	210
10	AMX-10RC	W+CTIS	15.88	233
11	Panther	W+CTIS	14.0	242
12	Pandur	W+CTIS	13.5	266
13	Saxon	W	11.66	332
14	LAV-25	W	12.79	345
15	Fuchs	W	19.0	366
16	Grizzly	W	10.5	371

W = wheels   T = tracks

Table 1-5 Overall Vehicle Trafficability Ranking on Clay

The rank order presented in Table 1-5 indicates immediately that, on average, the trafficability of tracked vehicles (shown in **bold** typeface) on clay is higher than that of wheeled vehicles in this weight range. However, with the benefit of CTIS, a suitably designed modestly armoured wheeled AFV can compete with the heavier tracked vehicles. Figure 1-1 however suggests that, weight for weight, tracked vehicles still have the advantage. In Table 2 their advantage is depicted as decisive by some parameters, such as NGP, (see graph 1E1 in Annex 1E) but not clear cut by, for example, the Maclaurin MMP parameter (see graph 1E5 in Annex 1E). The extent to which wheeled vehicles can compete with tracked vehicles in soft soil trafficability in the combat mass range 10-25 US ton is thus debatable.

Additional Observations

When it comes to selecting a vehicle on the basis of trafficability predictions, the results of this study reveal a procurement officer's nightmare. The relative merits of different vehicles appear to depend largely on the parameters chosen.

When procuring an AFV designed to meet a statement of requirement, these results indicate that the design of its running gear will probably be influenced by the trafficability criterion adopted in the statement of requirement. This means that it is very important for the customer to select the most appropriate parameters.

The variability in the various methods is a consequence of attempts to simplify what is a very complex problem. Most of the parameters commonly used in soft-soil trafficability prediction are based on data which rely on cone index as a measure of soil strength. It is well known that this is inadequate and leads to a situation where most of the parameters are derived from regression analysis of very scattered data, thereby incurring high levels of uncertainty.

1.1.6.2 Trafficability on Sands

The literature survey indicated that it is generally recognised that predictions of trafficability on sand are even less reliable than those on clay. A reasonable amount of work has been done, both in the field and under laboratory conditions, which has revealed that the methods developed for clay are not very effective for sand. Therefore a separate module was written in the computer programs for coarse grained soils. The predictions were based on the mobility numerics approach using equations embodied in NRMM II, and on those obtained from other sources which were felt to be reasonably reliable within the limits one can expect in terramechanics.

An inspection of the results in Table 1-3 indicates that tracked vehicles appear to have an overwhelming advantage on sand. Not only are they consistently at the top of the rank order but the gap in predicted capability between tracks and wheels is considerable. Indeed, the wheeled vehicles without CTIS appear to be immobile on the weaker of the two sands investigated. According to the Rowland and Harding prediction, wheeled AFVs with CTIS can approach the capability of tracked vehicles but this is not supported by the other predictions.

Interestingly, the predicted performance of the tracked vehicles appears to be very consistent, with little to choose between them. However, the wheeled vehicles exhibit a much greater variation in capability, those vehicles equipped with CTIS producing the best results (see Graphs 1E11 and 1E12 in Annex 1E). This is true on both the soft and firmer sands. For each type of vehicle the trafficability is relatively insensitive to combat mass, which reflects the essentially frictional characteristic of the soil.

The two values of penetrometer resistance gradient chosen for this study are based on two different types of sand in a reasonably dry condition which are approximately at the extremes of the range

of strengths found in practice (see [1.4]). It is recognised that penetration resistance gradient, on its own, is an inadequate descriptor of the properties of sand and this leads to the wide variation in measurements obtained under field conditions.

The 20% slip drawbar pull equation developed by WES, on the basis of their field measurements, and the methods employed in the NRMM give similar predictions, but these are very different to those of the equations of Rowland and Harding for gross traction and motion resistance of wheeled vehicles. The reason for this is not clear but it is reassuring that all three predict the same rank order.

1.1.6.3 Trafficability on Muskeg

The predicted values for VCI on muskeg were, on average, over twice as high for the wheeled AFVs as those for the tracked AFVs. However this is perhaps only of academic interest since typical cone index values for muskeg lie in the range 15 to 60 kPa. Hence, according to this prediction, even the best tracked vehicle in this sample, with a predicted VCI value of 133 kPa, would not be able to operate on muskeg. On this basis it seems unlikely that any normal AFV in the 10 to 25 US ton weight range would be mobile on this type of terrain.

1.1.6.4 General Observations

It should be noted that some of the vehicle dimensions used in this study were obtained by scaling from drawings where more reliable data were not available. This inevitably introduces some error but this is not thought to be very significant since the primary aim of this section is to compare methods of predicting soft-soil mobility rather than to identify the relative merits of the various vehicles chosen. In practice the weights of vehicles on military operations will normally be significantly different from those quoted in Janes [1.2] and, in any case, the trafficability predictions of these methods are subject to considerable levels of uncertainty.

Clearly there is much work to be done in improving methods of specifying and predicting soft soil trafficability. One of the fundamental limitations of the current empirical methods is the reliance on cone index as the only parameter for specifying soil strength. As has already been pointed out this is inadequate, although convenient. Unfortunately to do the job properly involves a great deal more complication (see Annex 1A). Perhaps the most promising way forward would be further development of the Wong theoretical model (see Annex 1B), which addresses this problem, accepting the added complexities in return, hopefully, for greater credibility. This approach has already been tried in the design and development of the ASCOD infantry fighting vehicle (see Wong [1.5]). It would be very interesting to trial this vehicle alongside others to determine whether the advantages claimed are realised in practice. Undoubtedly much work needs to be done to fully validate the existing tracked vehicle model and to develop a compatible model for wheeled vehicles. Complex computer models are becoming acceptable as procurement tools, as is demonstrated by the wide acceptance of the NRMM.

1.1.7 CONCLUSIONS

The following conclusions are relevant to armoured fighting vehicles in the 10-25 US ton range with approximately uniform weight distribution and, in the case of wheeled vehicles, all wheels driven.

Trafficability prediction is a very inexact science with a confusing array of methods.

The predictions indicate that the trafficability of tracked AFVs on clays tends to decrease with increase in combat weight. This trend is not so apparent in the case of wheeled AFVs.

Overall, the various methods predict that, for a given combat weight, tracked AFVs offer substantially higher levels of trafficability on clays than wheeled AFVs without CTIS, and significantly higher levels than wheeled vehicles equipped with CTIS.

On coarse-grained soils (sands) the advantage of tracked running gear appears to be overwhelming.

On fine-grained soils (clays) the extent of this predicted advantage depends on the parameter chosen to quantify trafficability.
In the procurement of new families of AFV, the trafficability parameters chosen in the statement of requirement will probably have a significant influence on the design of the running gear.

The choice of trafficability parameter could strongly influence the decision between tracked and wheeled running gear and an unwise choice could lead to an inappropriate outcome.

It is not possible to state definitively which method or parameter is the most reliable, however the indications are that:

i NGP is probably the least credible.

ii VCI based on field measurements should be reliable for fine grained soils but cannot be used to assess vehicles at the design stage.

iii VCI estimates based on MI calculation can be used at the design stage but the method does not have a firm scientific foundation.

iv MMP appears to be quite reliable for tracked vehicles on fine-grained soils, but less so for wheeled vehicles. The Rowland formula for wheels should not be used to compare wheeled and tracked vehicles. The Maclaurin formula is designed to overcome this limitation, but may be too flattering towards wheeled vehicles.

v VLCI has a sound scientific basis but, when compared to other methods, seems to be unduly favourable to wheeled vehicles.

vi Mobility numerics offer a logical way of rationalising experimental data but there is a confusing array of empirical equations and its reliance on CI to characterise the soil is an inherent limitation.

There is a need for more field data on the trafficability of modern vehicles in this weight range. However properly designed trials are very expensive to conduct.

Predictions using the NRMM reflect several additional vehicle characteristics other than soft-soil mobility. The accuracy of the soft-soil mobility component is only as good as the VCI system used for fine grained soils and the mobility numerics system used for coarse grained soil.

When using the NRMM for specifying mobility in a statement of requirement, the terrain file which is specified should reflect the type of terrain on which the vehicle will be expected to operate. This will usually imply running the model for more than one type of terrain.

1.2 OBSTACLE CROSSING

Obstacles on the battlefield appear in a wide variety of shapes and sizes. They can be non-deformable or deformable depending on the nature of the terrain and on its condition, which is usually strongly dependant on the weather. It is not practicable to attempt to measure the capability of an AFV on all types of obstacle. In fact it is very difficult to provide a repeatable test on deformable obstacles and therefore it is usual to specify and assess obstacle crossing ability using solid obstacles, the most fundamental and widely employed of which are the step and the trench. The capability of an AFV over these two gives a good indication of its obstacle crossing qualities. There is evidence that, at least in the case of wheeled vehicles, the vehicle design parameters which give a good capability over rectangular obstacles also promote good performance over obstacles of a more general profile (see [1.6]). However the ability of a vehicle to overcome a non-deformable obstacle of a given shape does not guarantee success over an identical obstacle which is deformable.

The analysis of deformable obstacle crossing poses difficult problems which have not yet been fully overcome. Rigid step and ditch crossing is much easier to analyse but, even here, there are difficulties in modelling exactly the behaviour of tyres and tracks.

1.2.1 STEP CLIMBING

1.2.1.1 Tracked Vehicles

There are three ways in which a tracked vehicle can be defeated by a rigid step:

Insufficient Sprocket Torque
There may be insufficient sprocket torque available from the power train to haul the vehicle over the obstacle. The initial torque requirement in a tracked vehicle is modest, even when it encounters a step higher than the front sprocket/idler centre height. This is because the sprocket/idler is mounted on the hull and hence the vertical force developed at the wall is applied directly to the hull and, to initiate the manoeuvre, it has only to overcome the pitch stiffness of the suspension system, which is comparatively low in a tracked vehicle. It is only when the roadwheels begin to lift off the ground that the sprocket torques begin to rise more sharply, peaking as the front roadwheels surmount the obstacle (see [1.7]). If the power train is not capable of delivering this peak torque then the vehicle will fail to overcome the obstacle. It is unlikely that a modern tracked AFV will be limited in this way.

Insufficient Traction
There must be sufficient frictional grip between the tracks and the ground and between the tracks and the obstacle to successfully complete the manoeuvre. Therefore in icy or muddy conditions performance may well be impaired, though aggressive tracks can go a long way to overcoming this problem.

Vehicle Geometry
The most likely cause of failure of a modern tracked vehicle to surmount a step is that, due to the vehicle geometry, the mass centre cannot reach a position directly above the step (see Figure 1-2). This occurs when the step is higher than a critical value which depends on the location of the roadwheels and of the rear sprocket/idler. It also depends on the height and longitudinal location of the mass centre and on the stiffness and bump travel of the suspension.

A computer model called USTEPT has been written to investigate the influence of these parameters. It assumes that the tracks offer ample adhesion and that the power train delivers sufficient torque to overcome the obstacle. It calculates the values of d_1 and d_2 shown in Figure 1-2 for increasing hull pitch angles and solves the geometric equations iteratively to identify the maximum step height for which the vehicle mass centre can pass over the vertical face of the step (i.e. when d_1 equals d_2 in Figure 1-2) An estimate of the deflection of the suspension system at the step can be entered into the model.

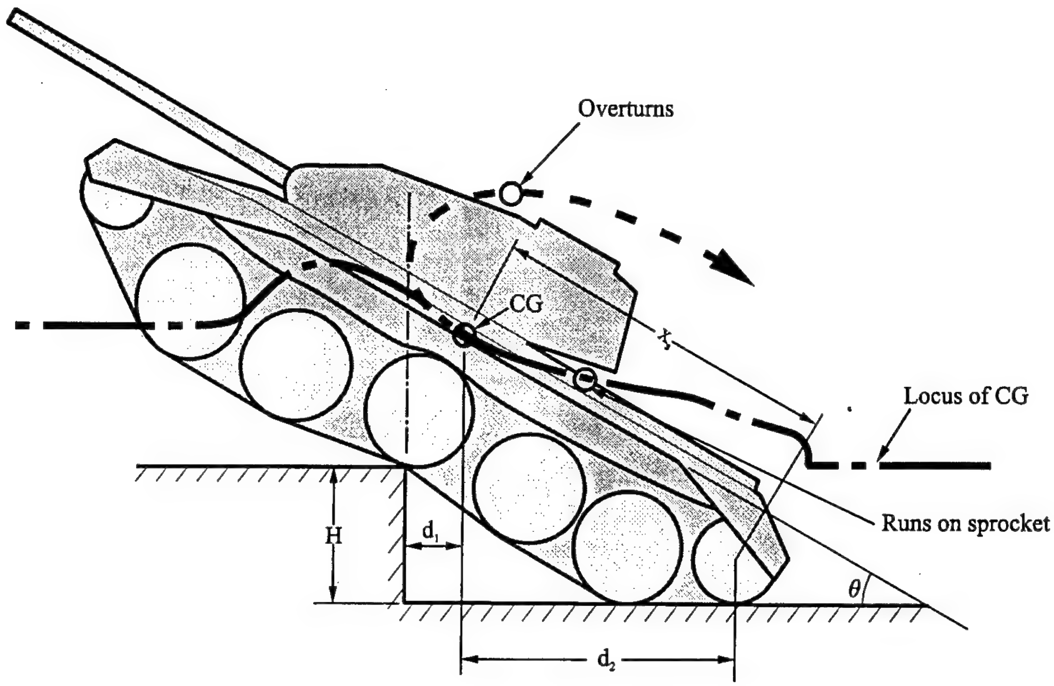


Figure 1-2 Tracked AFV Step Climbing

By entering data for a number of tracked vehicles in the weight range 10-25 US ton, it became apparent that the limiting condition occurs when the rear roadwheels have left the ground and the vehicle is supported at the rear by the sprocket/idler, which has no suspension system and therefore cannot deflect. It should be noted that this analysis was based on estimated co-ordinates for the mass centre since such data is not readily available from published sources. However, from comparisons with vehicles for which the mass centre location is known, these estimates are judged to be credible.

An attempt was made to forecast the step climbing capability of the tracked vehicles chosen for the trafficability study. The results are shown in Table 1-6.

Manufacturer	Vehicle Type	ESTIMATED PARAMETERS CG Height (m)	a/L	Track deflection (m)	Predicted Step (m)	Quoted Step (m)
Giat	AMX-10P	1.2	0.5	0.15	0.69	0.7
United Defense	M113-A1	1.2	0.55	0.125	0.65	0.635
Steyr	SK105-A1	1.35	0.5	0.15	0.96	0.8
Alvis	Stormer	1.2	0.55	0.1	0.61	0.6
	BMP-3	1.2	0.55	0.1	0.93	0.8
	M108	1.4	0.55	0.1	0.74	0.533
Giat/Hagglunds	CV90105	1.2	0.5	0.2	1.22	1.2

a/L = position of mass centre along trackbase

Table 1-6 Tracked Vehicle Step Climbing

It was quickly discovered that the predicted maximum step height is very sensitive to the estimated location of the vehicle mass centre and the estimate of suspension/track deflection at the centre wheelstations as the vehicle tips forward onto the top surface of the step. The predictions were, in most cases, arrived at by varying the estimated parameters until a reasonable agreement with the quoted step climbing capability was achieved. Where this process required unlikely values of these parameters (e.g. in the case of M108), only credible ones were used, leading to predictions well above the quoted capability. This suggested that, in such cases, the limitation on step climbing is power train or adhesion related rather than due to vehicle architecture.

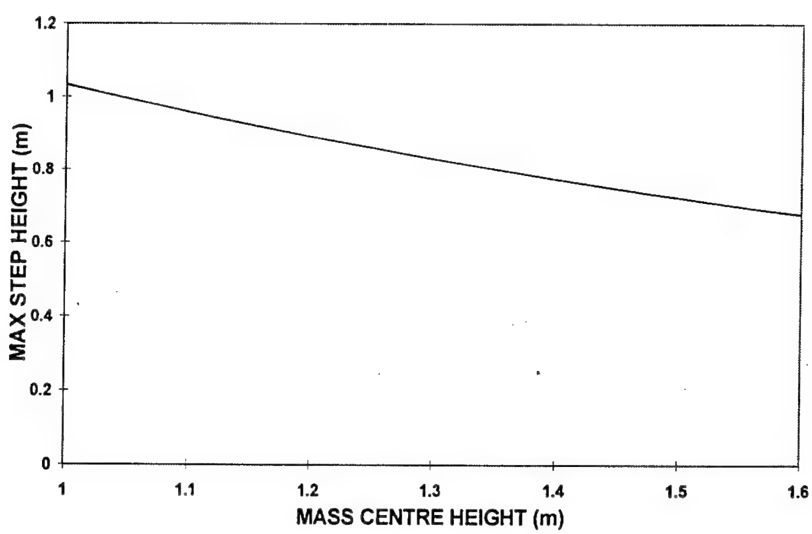


Figure 1-3 Effect of Mass Centre Height on Step Climbing

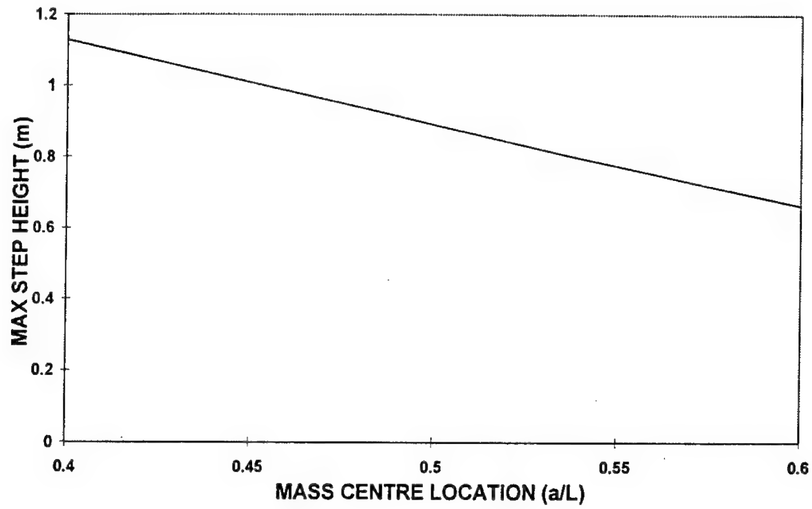


Figure 1-4 Effect of Longitudinal Location of Mass Centre on Step Climbing

The computer model was then used to examine the sensitivity of the predicted maximum step to the three parameters discussed above. The results are presented in Figures 1-3 to 1-5. In Figure 1-4, a is the distance from the axis of the front roadwheel to the vehicle mass centre, and L is the trackbase (length of track on ground). Therefore the abscissa represents the longitudinal location of the mass centre from the front wheelstations expressed as a proportion of the trackbase.

It can be seen that a mass centre which is low and forward of the mid trackbase position is advantageous. Also large suspension deflections at the central wheelstations under the weight of the vehicle are beneficial (see Figure 1-5). This favours vehicles with large suspension travel and soft suspension.

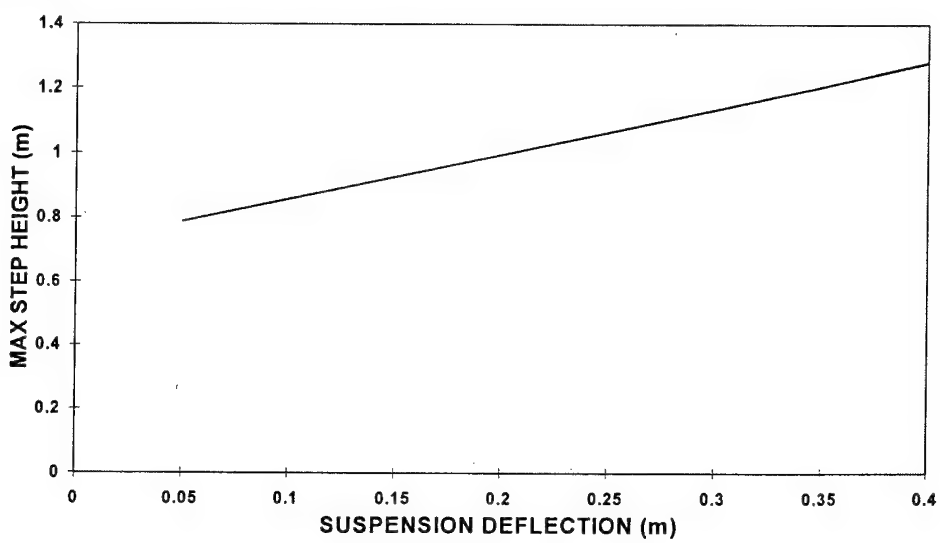


Figure 1-5 Effect of Suspension Deflection on Maximum Step Height

1.2.1.2 Wheeled Vehicles

A wheeled vehicle may be defeated by a step for the same reasons as a tracked vehicle. In the discussion which follows it is assumed that a wheeled AFV has an adequate approach angle and that it employs an all-wheel drive system. This will perform better than one with an undriven front axle.

Insufficient Driveline Torque
There may be insufficient driveline torque available from the power train to propel the vehicle over the step. The tractive effort required in a wheeled vehicle to initiate a step climbing manoeuvre increases as the height of the step is raised up to the point where it equals the radius of the front tyres.

In the case of a two axle vehicle, a step higher than this demands sufficient front wheel torque to generate a vertical force able to lift the front of the vehicle bodily off the ground. This force is higher than that required of a tracked vehicle of similar mass, having a conventional leading sprocket/idler, in an equivalent situation. There must also be sufficient tractive force at the rear axle to generate a reaction on the face of the step large enough to develop this vertical force by the mechanism of friction.

The torques required will depend on the weight of the vehicle, the position of its mass centre, the wheel radius and the coefficients of adhesion. A rear-heavy weight distribution will clearly be advantageous when the front axle is climbing up the step and a front-heavy distribution will facilitate the rear axle surmounting the step. The step climbing of modern AFVs will probably not be limited by such power train considerations.

When faced with high steps, multi-axle vehicles behave a little more like tracked vehicles except that the vertical forces at the front are applied to the wheels and transmitted to the hull through the suspension system, rather than directly via a front sprocket/idler.

Insufficient Traction
There may be insufficient adhesion between the tyres and the ground and the tyres and the step to generate the forces necessary to overcome the obstacle. For steps higher than tyre radius, good adhesion becomes vital. Wheeled AFV tyres are chosen to give a compromise between on and off-road qualities and therefore are usually less aggressive than tracks, a fact which can render them less able to deal with low adhesion conditions.

Hull Hang-Up
Once the front axle has surmounted the step there is the possibility that the hull will "hang up" on the obstacle. This usually dictates the limit for 4x4 vehicles, whose maximum step capability is usually only slightly greater than the ground clearance under the hull just ahead of the rear axle (see Figure 1-6). A short wheelbase vehicle will generally have a small advantage over one with a long wheelbase, due to the larger pitch angle of the hull. Multi-axle vehicles will suffer less from this problem, and their capability will depend on axle spacing and whether they use interconnected bogie or independently suspended axles. Equi-spaced and close coupled axles will give the best results, perhaps removing the possibility of this mode of failure.

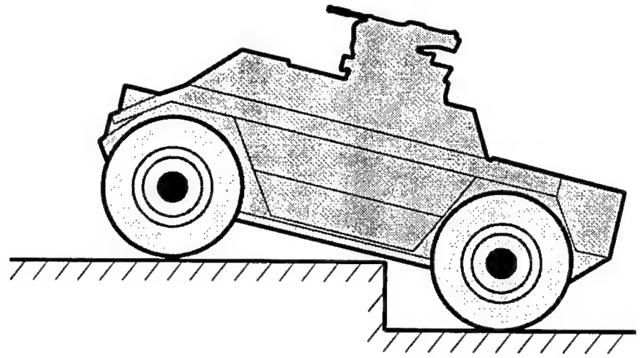


Figure 1-6 Step Climbing Failure of a Two-Axle Vehicle

Vehicle Geometry
The vehicle may overturn backwards before it surmounts the step. If the step is sufficiently high, the geometry may prevent the vehicle centre of gravity moving sufficiently far forward to pass the edge of the step. In this situation the vehicle cannot tip over onto the top surface of the step. Wheeled vehicles will often have a higher mass centre than equivalent tracked vehicles, and do not have the advantage of a sprocket/idler at the extreme rear of the vehicle. However in compensation, the fact that the rear wheelstations have suspension means that the vehicle benefits from the action of the suspension on rebound as the vehicle is on the point of surmounting the step. A centre of gravity forward of the mid-wheelbase position is advantageous in this respect.

A survey of wheeled AFV step climbing ability was carried out using data from Janes [1.2]. Not surprisingly it was found that the quoted maximum step capability of two-axle vehicles was only slightly greater than the ground clearance under the hull.

For multi-axle vehicles the results are shown in Table 1-7 For most of the vehicles examined, the quoted maximum step height is no greater than 55% of the tyre diameter, i.e. slightly higher than the axis of the axles. For the majority, even those with uneven axle spacing, hang-up does not appear to be a problem as is evidenced by the ratio of step to ground clearance, which in most cases is appreciably greater than unity. A few vehicles appear to have a far superior step capability than average. These have been highlighted in bold type. Interestingly, all of these are French. Closer inspection reveals that they are equipped with hydrogas suspension components with a jacking capability, on all or some of the axles. It is assumed that this facility can be employed to enhance step climbing capability. Other vehicles fitted with hydrogas suspension do not appear to have above average step climbing ability.

Manufact	Type	Axles	Quoted Step Ht (m)	Ground Clearance (m)	Tyre Diameter (m)	Ratio Step to Ground Cl	Ratio Step to Tyre Dia
Panhard	VCR/TT2	3 (uneven)	**0.8**	0.375	1.066	**2.133**	**0.750**
Reumech	Ratel 20	3 (uneven)	0.6		1.254		0.478
Henschel	Fuchs	3 (uneven	0.6	0.506	1.254	1.186	0.478
SIBMAS		3 (uneven)	0.7	0.4	1.254	1.750	0.558
	Tatrapan	3 (uneven)	0.6	0.39	1.295	1.538	0.463
	G6	3 (uneven)	0.5	0.45	1.48	1.111	0.338
Panhard	Sagai	3 (uneven)	**0.8**	0.45	0.984	**1.778**	**0.813**
Cad Gage	LAV-300	3 (uneven)	0.609	0.533	1.245	1.143	0.489
Renault	VBC90	3 (even)	0.5		1.254		0.399
Steyr-D-P	Pandur	3 (even)	0.5	0.43	1.124	1.163	0.445
Santa Bar	BMR-600	3 (even)	0.6	0.4+	1.155	1.333	0.519
Alvis	Saracen	3 (even)	0.46	0.426	1.118	1.080	0.411
Giat	AMX10RC	3 (even)	**0.8**	0.2-0.6	1.254		**0.638**
Norinco	WZ551	3 (even)	0.5	0.41	1.254	1.220	0.399
Komatsu	Type 87	3 (even)	0.6	0.45	1.254	1.333	0.478
Giat	VAB	3 (even)	0.6	0.5	1.254	1.200	0.478
GM Can	LAV-25	4 (uneven)	0.5	0.5	0.984	1.000	0.508
Henschel	Luchs	4 (uneven)	0.6	0.506	1.254	1.186	0.478
	BTR 80	4 (uneven)	0.5	0.475	1.118	1.053	0.447
	OT-64	4 (uneven)	0.5	0.46	1.118	1.087	0.447
Giat	Vextra	4 (uneven)	**1.0**		1.328		**0.753**
	Rooikat	4 (uneven)	0.6	0.49	1.343	1.224	0.447
Mowag	Piranha III	4 (uneven)	0.6	0.595	1.035	1.008	0.580
Mowag	Piranha III	5 (uneven)	0.6	0.595	1.035	1.008	0.580

Table 1-7 Wheeled Vehicle Step Climbing

1.2.2 TRENCH CROSSING

Trench crossing ability of wheeled AFVs depends to a large extent on the number of axles and their position along the length of the vehicle. It is usually quoted for the case where the vehicle approaches the trench in a direction perpendicular to its edge. However it is sometimes given for an oblique crossing, but this is not always clearly stated.

1.2.2.1 Wheeled Vehicles

Two-Axle Vehicles

A two axle vehicle will fail to cross a trench if the wheels on (usually) the leading axle drop into the trench (see Figure 1-7). This will certainly occur if the trench is wider than the diameter of the tyres. If the trench is only slightly narrower than the tyre diameter, the tyres will probably be forced into the trench, under the action of the axle load, and become wedged. To prevent this the trench will have to be significantly narrower than the tyre diameter, but not narrower than the diameter of the wheel rims.

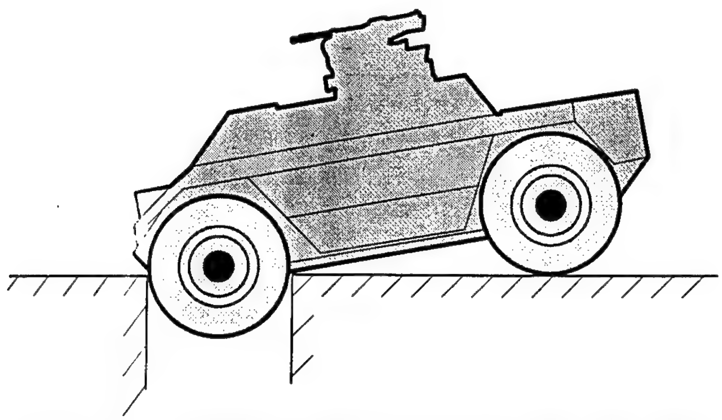


Figure 1-7 Trench Crossing Failure of Two-Axle AFV

Examination of Janes [1.2] reveals that trench crossing capabilities are rarely quoted for two axle vehicles. Table 1-8 shows those which are available. However it is clear that the mode of failure is likely to be the same as that of three axle vehicles for which a significant amount of data is available. On the basis of the analysis of three-axle vehicles (see below) the trench crossing capabilities of two-axle AFVs fitted with pneumatic tyres should be consistent with the equation,

$$\text{Max trench width} \leq d_w + 1.6\,h$$

where d_w is the wheel diameter and h is the tyre section height. Obviously, if the tyres are deflated, this performance would not be achieved. Values predicted by this equation are shown in Table 1-8 and compared with those quoted in Janes [1.2].

Vehicle Builder	Type	Tyre Diameter (m)	Tyre Section ht (m)	Wheel Diameter (in)	Quoted Trench (m)	Predicted Trench (m)
Panhard	VBL	0.864	0.228	16	0.5	0.77
Reumech	Eland	1.016	0.305	16	0.5	0.89
Cad Gage	Scout	1.321	0.394	21	1.14	1.16
Kader	G320	0.787	0.19	16	0.6	0.71
Reumech	Casspir	1.219	0.355	20	1.06	1.08
Reumech	Kobra	1.144	0.318	20	1	1.02
	Mamba	1.143	0.317	20	0.9	1.02

Table 1-8 Trench Crossing Capability of Two-Axle AFVs

Three-Axle Vehicles

A three-axle vehicle, approaching the trench perpendicularly, will suffer the same mode of failure as that of a two axle vehicle (see Figure 1-8). If the mass centre is ahead of the second axle, the front axle will drop into the trench. If it is behind the second axle than the rear axle will suffer this fate. The trench crossing capability of three-axle AFVs is consistent with the equation

$$\text{Max trench width} \leq d_w + 1.6\,h$$

using the notation given in the section above. The coefficient of 1.6 in the last term of the equation was derived from a survey of the quoted trench crossing ability of three-axle wheeled

AFVs listed in Janes [1.2] (see Table 1-9)

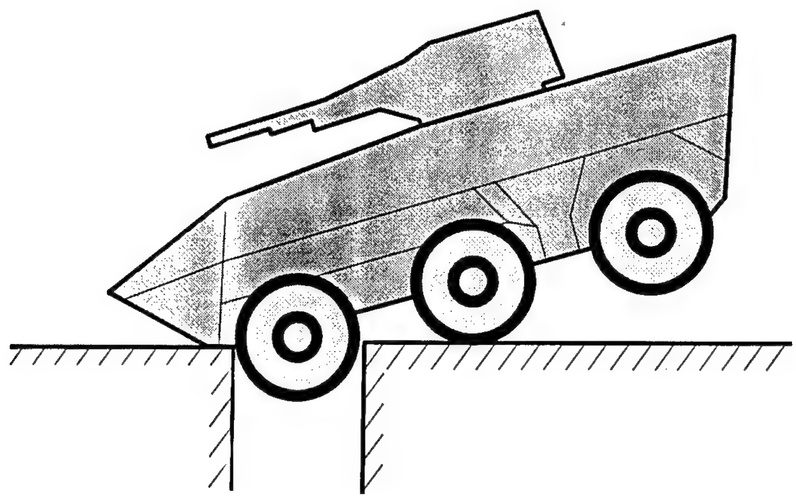


Figure 1-8 Trench Crossing Failure of Three-Axle AFVs

It may be possible to cross a wider trench by approaching it at a suitable oblique angle. For best results this angle should be parallel to the diagonal connecting the contact patches of the two axles which are the most closely spaced (see Figure 1-9). This technique will only work if:

In the case where the two front axles are closest together, the mass centre is behind the mid point between these axles.

In the case where the two rear axles are closest together, the mass centre is ahead of the mid point between these axles.

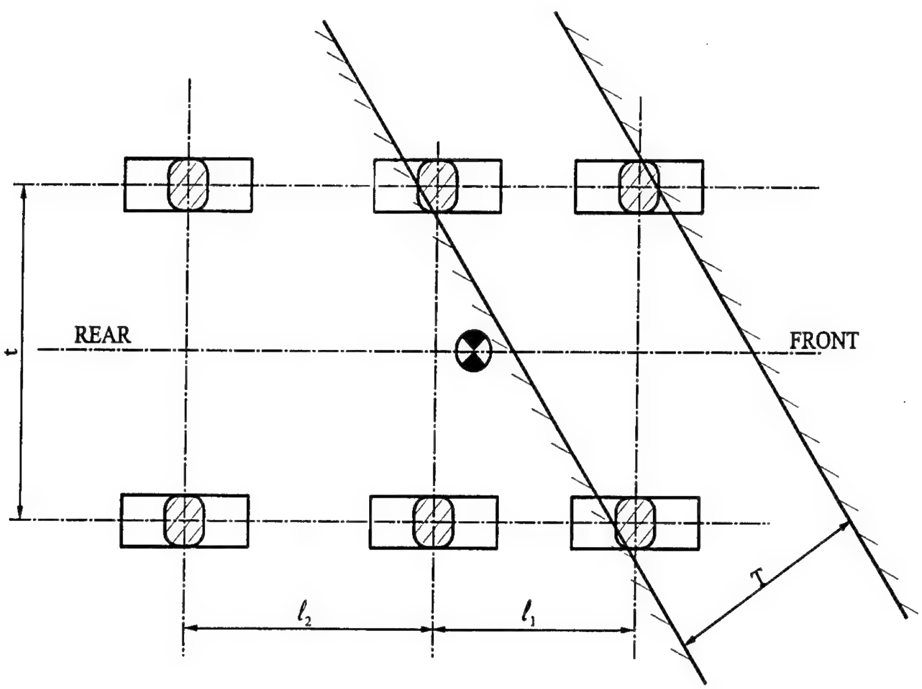


Figure 1-9 Effect of Oblique Approach for Three-Axle AFVs

A survey of wheeled AFVs listed in Janes [1.2] suggests that the quoted trench crossing capability

of three-axle AFVs using the oblique crossing technique is consistent with the equation,

$$\text{Max trench width} \leq 0.3d + \frac{t \times l_{min}}{\sqrt{t^2 + l_{min}^2}}$$

where d = tyre diameter, t = track, l_{min} = minimum axle spacing. The first term allows for the contribution of the tyre diameter, the coefficient of 0.3 being based on data from the survey (see Table 1-9).

Vehicle Manufacturer	Type	Axles	Min Axle Spacing (m)	Track (m)	Tyre Diameter (m)	Tyre Section ht (m)	Wheel Diameter (in)	Ditch - Perpendicular Quoted (m)	Ditch - Perpendicular Predicted (m)	Ditch - Oblique Quoted (m)	Ditch - Oblique Predicted (m)
GM Can	Grizzly	3 (uneven)	1.04	2.2	0.984	0.289	16	0.406	0.87		1.27
Reumech	Ratel 20	3 (uneven)	1.4	2.08	1.254	0.373	20	1.15	1.11		1.58
Henschel	Fuchs	3 (uneven	1.75	2.55	1.254	0.373	20	1.1	1.11		1.86
SIBMAS		3 (uneven)	1.4	2.07	1.254	0.373	20		1.11	1.5	1.57
Panhard	VCR/TT	3 (uneven)	1.425	2.35	0.984	0.289	16		0.87	1.1	1.54
Panhard	Sagai	3 (uneven)	1.22	2.135	0.984	0.289	16		0.87	1.1	1.38
	G6	3 (uneven)			1.48	0.533	25	1	1.49		
Renault	VBC90	3 (even)	1.5		1.254	0.373	20	1	1.11		
Steyr-D-P	Pandur	3 (even)	1.53	2.08	1.124	0.308	20	1.1	1.00	1.6	1.60
Santa Bar	BMR-600	3 (even)	1.65	2.08	1.155	0.324	20		1.03	1.5	1.67
Alvis	Saracen	3 (even)	1.524	2.083	1.118	0.305	20		1.00	1.52	1.60
Giat	AMX10RC	3 (even)	1.55	2.425	1.254	0.373	20		1.11	1.65	1.72
Norinco	WZ551	3 (even)	1.9		1.254	0.373	20	1.2	1.11		
Komatsu	Type 87	3 (even)	1.5		1.254	0.373	20		1.11	1.5	
GM Can	LAV-25	4 (uneven)	1.1	2.2	0.984	0.289	16	2.057	1.97		1.31
Henschel	Luchs	4 (uneven)	1.4	2.54	1.254	0.373	20	1.9	2.51		1.64
	BTR 80	4 (uneven)	1.35	2.41	1.118	0.33	18	2	2.34		1.55
	OT-64	4 (uneven)	1.3	1.86	1.118	0.33	18	2	2.29		1.43
Giat	Vextra	4 (uneven)	1.7	2.554	1.328	0.384	22	2.3	2.87		1.85
	Rooikat	4 (uneven)	1.55	2.415	1.343	0.417	20	2	2.73		1.75
Mowag	Pirhana III	5 (uneven)	1.1	2.2	1.035	0.263	20	2	2.03		1.33

Table 1-9 Wheeled AFV Trench Crossing Capability

Four-Axle Vehicles

In the case of four-axle vehicles, failure to cross a trench occurs when the closest spaced pair of leading or trailing axles drops into the trench as shown in Figure 1-10. This assumes that the vehicle mass centre lies between the second and third axles. It would be very unusual for this condition not to be met in this type of vehicle. The trench crossing performance of four-axle vehicles appears to be consistent with the equation,

$$\text{Max trench width} \leq l_{min} + d_w + 1.6\,h$$

where l_{min} = minimum spacing between axles 1 and 2 or between 3 and 4, d_w = wheel rim diameter and h = tyre section height. The coefficient of 1.6 in the last term of the equation was derived from a survey of the quoted trench crossing capability of a range of four-axle AFVs listed in Janes [1.2] (see Table 1-9)

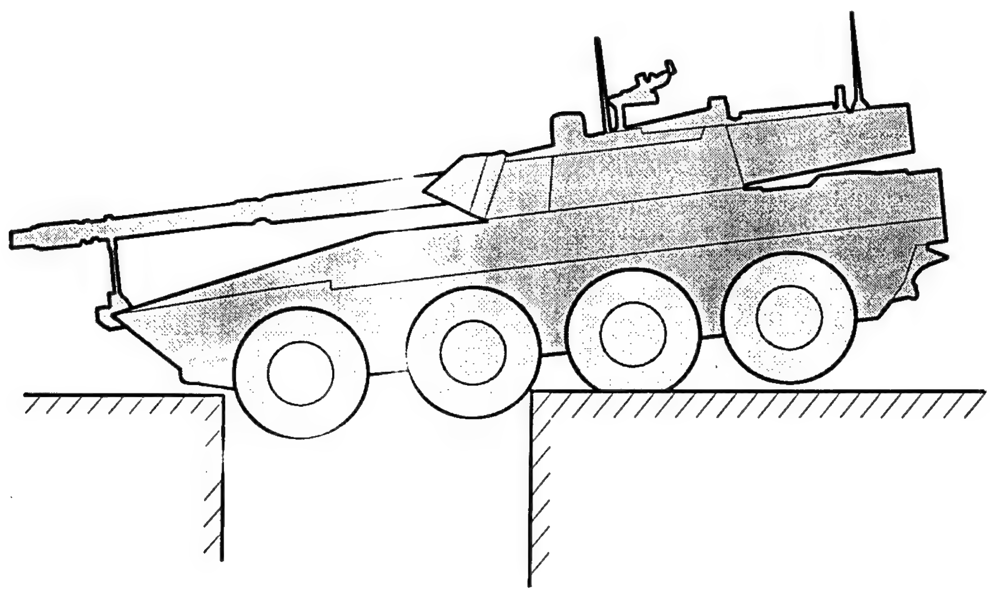


Figure 1-10 Trench Crossing Failure of a Four-Axle AFV

The oblique approach technique offers no advantage for vehicles of this type as is apparent from Table 1-9.

Five or More Axle Vehicles

Five-axle wheeled AFVs are extremely rare, only one modern example being known to the author. The trench capability of this type of vehicle, when approaching the trench perpendicularly, will be governed by the same equation as that of a four-axle vehicle. It is unlikely that AFVs with more than five axles will be encountered. The oblique approach will offer no advantage.

Wheeled vehicles with six or more axles should offer an improved trench crossing capability, but this type of architecture is not currently used on AFVs.

1.2.2.2 Tracked Vehicles

The trench crossing capability of tracked AFVs benefits from two features. Firstly the track tends to prevent groups of wheels dropping into the trench in such a manner that they immobilise the vehicle, since it provides a form of ramp up which the wheel can climb as it reaches the far side of

the trench. Secondly, where the track is of the conventional tensioned type utilising both sprockets and idlers, the extra "reach" of these components, ahead of and behind the front and rear roadwheels respectively, extends the width of trench which can be crossed.

Odd Number of Wheelstations per Side

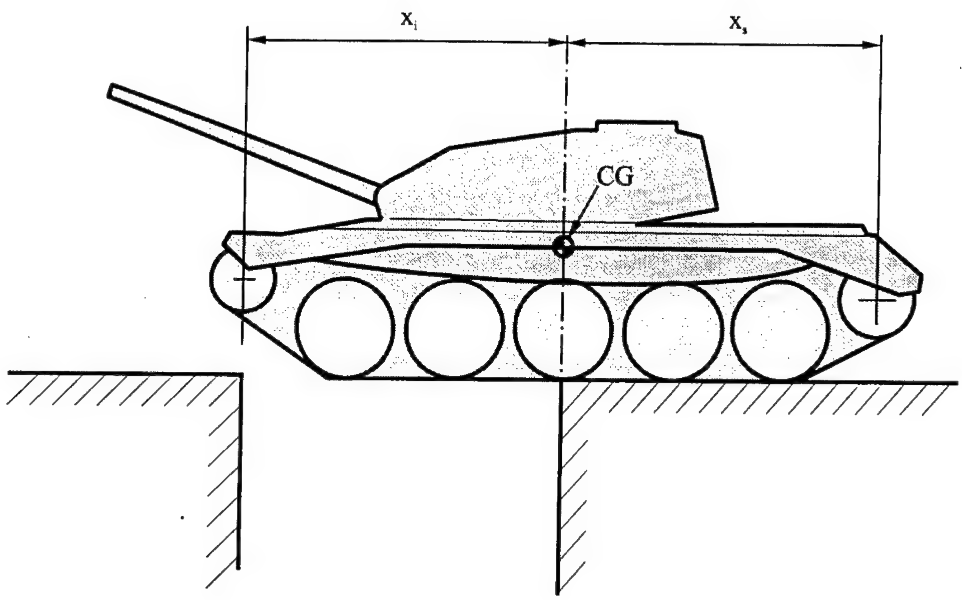


Figure 1-11 Trench Crossing - Odd Number of Wheelstations per Side

For a tracked AFV having an odd number of wheelstations on each side, the best results would be expected when the mass centre is directly above the centre wheelstations (see Figure 1-11). For this type of vehicle the trench capability is given by the lesser of x_i and x_s or approximately by the formula,

$$\text{Max trench width} \leq L_{is} / 2$$

where L_{is} $(= x_i + x_s)$ is the distance between idler and sprocket centres.

Even Number of Wheelstations per Side

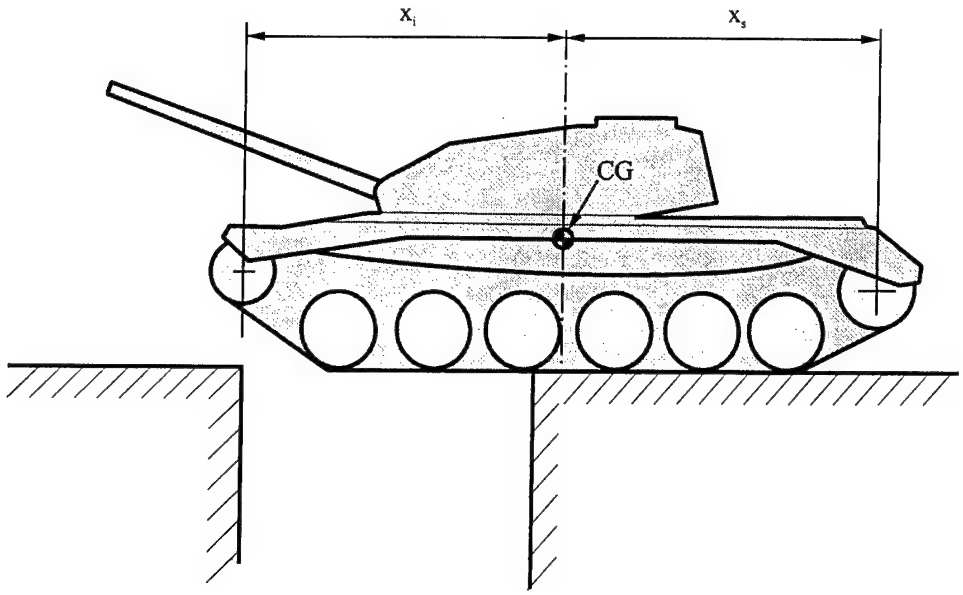


Figure 1-12 Trench Crossing – Even Number of Wheelstations per Side

With an even number of equi-spaced wheelstations per side, assuming that the vehicle mass centre lies between the two middle wheelstations, the trench crossing capability will be a little less than an equivalent vehicle with an odd number of wheelstations. This is because, as soon as the wheelstation ahead of the mass centre passes the edge of the trench, there will be a tendency for the vehicle to pitch forward into the trench (see Figure 1-12). A suitable equation would be,

$$\text{Max trench width} \le L\left(\frac{0.5n-1}{n-1}\right)+0.5(x_i-x_f)+0.2d$$

where L is the length of track on the ground, n is the number of wheelstations per side, x_i is the front sprocket/idler to CG distance, x_f is the front road wheel to CG distance and d is the roadwheel diameter.

The coefficient of 0.2 in the last term of this expression was derived from a survey of the quoted trench crossing capability of a range of tracked AFVs taken from Janes [1.2].

Predicted and Quoted Trench Crossing Capability

The predictions of the empirical formulae given above were compared with the quoted trench crossing capability of a range of tracked AFVs. The results are presented in Table 1-10 and Figure 1-13.

Manufacturer	Vehicle Type	Wheels per Side	Wheel Diameter (m)	Track on Ground (m)	Sprocket-Idler Dist (m)	Predicted Trench (m)	Quoted Trench (m)
Giat	AMX-10P	5	0.597	2.93	4.178	2.09	2.1
United Def	M113	5	0.52	2.667	3.96	1.98	1.68
Giat	MXF3	5	0.57	2.997	2.997	1.50	1.5
Steyr	SK105/A1	5	0.55	3.037	4.804	2.40	2.41
Alvis	Stormer	6	0.584	3.12	3.798	1.70	1.75
United Def	LP M8	6	0.59	3.61	5.06	2.29	2.133
Cad Gage	Stingray	6	0.53	3.632	5.45	2.47	2.13
Iveco	Hitfist	6	0.6	3.87	5.5	2.48	2.5
United Def	Bradley	6	0.64	3.912	5.43	2.45	2.54
	BMP-3	6	0.55	4.06	5.58	2.49	2.5
	M108	7	0.6	3.962	5.28	2.64	1.828
Giat/Hagg	CV90105	7	0.6	3.98	5.54	2.77	2.9

Table 1-10 Tracked Vehicle Trench Crossing Capability

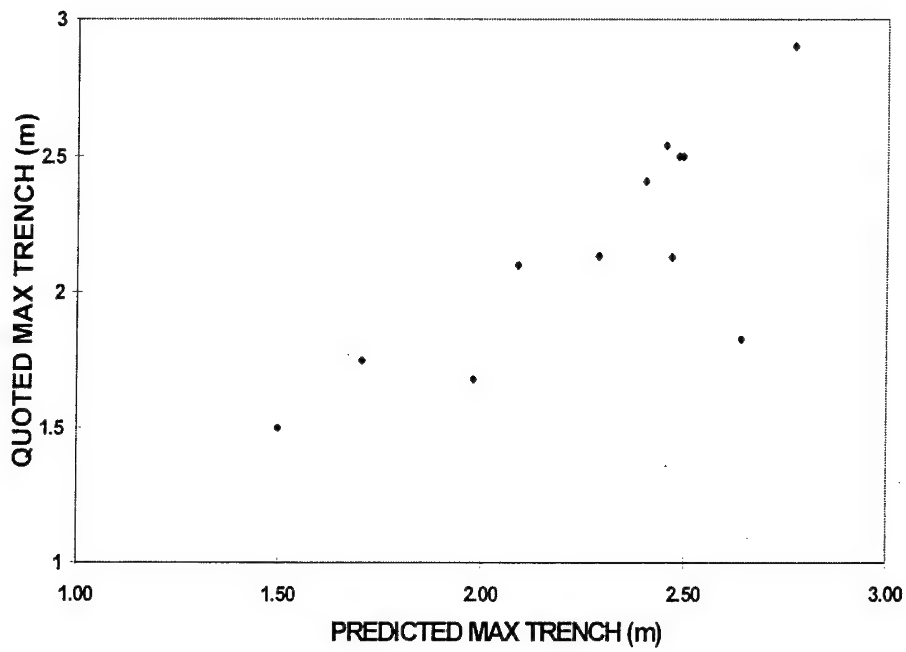


Figure 1-13 Comparison of Predicted and Quoted Trench Crossing Capability

In Table 1-10 and Figure 1-13 the predicted trench crossing capability is an estimate of the best achievable within the geometrical limits of the track layout of each vehicle, assuming that the mass centre lies roughly above the centre of the trackbase. None of the quoted values exceeds this estimate significantly but quite a few fall below it. This is probably because, in these vehicles, the longitudinal location of the mass centre is some distance from the mid point of the sprocket to idler distance.

1.2.3 URBAN OBSTACLE CROSSING

A review of the literature revealed no reports on this topic. However two aspects of mobility over this type of terrain will be briefly discussed.

1.2.3.1 Dwarf Walls

When fighting in built up areas, the remains of the walls of destroyed buildings may need to be crossed by AFVs either taking short cuts or seeking cover. These *dwarf* walls appear in a variety of heights and widths, and clearly the higher the wall that can be overcome, the more options there are available to the vehicle commander.

Some AFV test tracks employ a range of standardised dwarf walls amongst their obstacle crossing test facilities. For example the French Defence Ministry test track at ETAS, situated at Angers, has six concrete dwarf walls of square cross section, ranging in height from 200 to 800 mm .

For tracked vehicles the height of dwarf wall which can be surmounted will be the same as the maximum step height, since the manoeuvre is in principle very similar. For wheeled vehicles it would be reasonable at first sight to use the same argument. However where the space between adjacent wheelstations is greater than the width of the dwarf wall, the maximum height of dwarf wall which the vehicle can overcome will be limited by the ground clearance under the hull. If it is higher than this the vehicle will tend to "hang up" (see Figure 1-14). This means that multi-axle vehicles with closely spaced wheelstations will have the best chance of success.

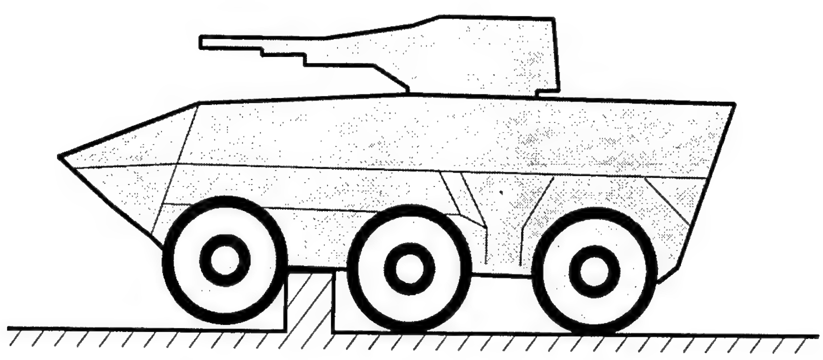


Figure 1-14 AFV Hang-Up on Dwarf Wall

1.2.3.2 Rubble

It would be reasonable to expect tracked vehicles to achieve greater success in overcoming piles of rubble resulting from the destruction of buildings. There are two obvious reasons for this. Firstly, the laying of a track over such an irregular surface will tend to minimise the displacement of the rubble and the likelihood of the running gear dropping into hollows resulting from cellars

and similar features. Secondly, the rubble may well contain metallic debris from pipes, reinforcing rods and structural steelwork which is very likely to puncture pneumatic tyres. Even where run-flat systems are fitted, this type of damage will degrade the mobility of a wheeled vehicle.

1.2.4 Further Observations

In some wheeled vehicles the geometry of the front end of the hull can be an aid to step climbing and trench crossing. If the nose of the hull protrudes beyond the front wheels, and the vehicle begins to topple into a trench it can land on, and be supported by, the lower surface of the nose (see Figure 1-10). If its angle of obliquity is sufficiently shallow there may be sufficient traction from the rear wheels to drive the vehicle forward until the front wheels can engage the far side of the trench, and the vehicle may be able to haul itself clear. This only works if several other parameters are favourable, and is not usually relied upon in practice. This technique can also slightly enhance step climbing, but the influence of nose design on approach angle must not be ignored.

In general, due to scale effects, the larger the vehicle the higher the step climbing and trench crossing capability. This means that within the battle group, Main Battle Tanks (MBTs) are likely to have a significantly superior obstacle crossing capability than Infantry Fighting Vehicles (IFVs), reconnaissance vehicles and utility vehicles which support them.

The NRMM incorporates an obstacle crossing module which predicts the ability of wheeled and tracked vehicles to overcome undeformable trapezoidal obstacles, either in the form of steps or ditches. This module determines the tractive requirements, the possibility of overturning and of fouling between the hull and the obstacle when the vehicle approaches at very low speed in a direction perpendicular to the edge.

This model suffers from a number of limitations, some of them serious. Having been developed for wheeled vehicles, it models a tracked vehicle as an "equivalent" two axle wheeled vehicle having very large wheels. There are guidelines on choosing this equivalent running gear, but this approach is unlikely to account adequately for the contribution of the rear sprocket/idler. It has already been noted that tracked AFVs are most unlikely to suffer from a "hang-up" failure, but the NRMM obstacle crossing module does not appear to rule this out for this type of vehicle. In addition the model takes no account of suspension deflection which has been shown to have a very significant effect on step climbing ability (see [1.7]). It is understood that there are proposals for a replacement obstacle crossing module which will address these problems.

1.2.5 Conclusions

The maximum step height surmountable by an AFV tends to increase in proportion to the size of the vehicle.

A mass centre which is low and situated forward of the centre of the trackbase or wheelbase is advantageous in step climbing capability. Soft suspension with generous travel is also beneficial.

For a given size, tracked AFVs offer inherently superior step climbing capability than wheeled AFVs due to their lower mass centre height, the benefit of a rear sprocket/idler and the fact that they will not "hang-up". With suitably aggressive tracks they are less limited by low-grip conditions.

Wheeled vehicles with two axles, and multi-axle vehicles with widely-spaced axles, are particularly poor on steps and are limited by ground clearance under the hull. The step climbing capabilities of multi-axle wheeled vehicles with closely-spaced axles are much better but size-for-size are inferior to those of tracked vehicles.

The maximum width of trench which an AFV can cross tends to increase in proportion to the size of the vehicle.

Due to the extreme location of the sprocket and idler, for a given size, tracked AFVs employing the normal type of tensioned track architecture offer trench crossing ability superior to that of wheeled AFVs.

For good trench crossing the longitudinal location of the mass centre should be close to the centre of the trackbase or wheelbase of the vehicle.

Tracked vehicles with an odd number of wheelstations on each side have a small advantage in ditch crossing ability over those with an even number, depending on the position of the mass centre.

Two and three-axle wheeled vehicles have poor trench crossing ability when approaching perpendicularly. It is limited by tyre diameter.

The trench crossing capability of a three-axle vehicle may be enhanced significantly by using an oblique approach technique, provided the longitudinal location of the mass centre is appropriate.

The trench crossing capability of four-axle wheeled vehicles is superior to that of two and three-axle vehicles. It is limited by the spacing of the closest axles and by the tyre diameter. The oblique approach technique offers no advantage.

Tracked vehicles are likely to offer superior capability in overcoming urban obstacles such as dwarf walls and rubble.

1.3 EFFECT OF SUSPENSION TYPE ON TERRAIN ACCESSIBILITY

The design of a vehicle suspension system has a significant influence on its terrain accessibility. A list of suspension system properties and their mobility implications follows. These properties and the comments made are entirely in the context of applications to AFVs in the weight range 10 to 25 US tons. Such vehicles will be expected to be capable of operation off-road which implies all-wheel drive systems for wheeled vehicles.

1.3.1 Suspension System Characteristics

Ground Clearance

Inadequate ground clearance can result in a significant mobility penalty. If suspension system components, or the underside of the hull, come into contact with the ground when traversing rough terrain, the resistance to motion of the vehicle is increased. This can easily result in complete immobilisation.

Suspension Travel

The suspension travel of the system can influence the obstacle crossing capability as has already been mentioned in Section 1.2. A large bump travel, in particular, can improve the step climbing capability by reducing the maximum pitch angle incurred by the vehicle as it surmounts the step. In wheeled vehicles, a high level of rebound travel at the rear wheelstations can also assist the vehicle in getting over the obstacle. Some AFV suspension systems, employing hydrogas technology, provide a variable ride height capability. This can be used to increase ground clearance thus improving trafficability on soft and particularly on rutted terrain.

Articulation

Suspension systems can be designed to incorporate interconnection between axles or wheels in order to spread the vehicle weight more evenly over the ground. This can confer advantages in reducing sinkage on soft terrain and hence reducing resistance to motion. Such systems used to be widely used on tracked vehicles and were not unusual on wheeled off-road vehicles. However, the current trend in AFVs is to employ independent suspension systems which incorporate no articulation.

There are vehicles, used commercially for moving heavy loads, which achieve almost complete articulation by the use of hydraulic interconnection of many wheelstations. They therefore spread the load evenly over undulating road surfaces. To maintain stability, computer control is normally used. This type of technology should enhance trafficability and, with suitable control of individual wheelstations, could aid obstacle crossing. However, it does not appear to have been tried in AFVs.

Suspension Load-Deflection Characteristic

In a vehicle without articulation, a soft suspension results in a more even distribution of weight over the ground, giving benefits in terms of soft-soil trafficability on rough terrain. However a soft suspension can result in excessive bump-stop impacts at high speed on rough terrain. To overcome this problem, rising rate or dual rate springs are commonly employed, but there is a cost in terms of trafficability.

Approach and Departure Angles

The positioning of the front and rear axles on a wheeled vehicle in relation to the hull will determine the magnitude of the approach and departure angles (see Figure 1-15). If these angles are too small the vehicle will have difficulty in surmounting large bumps, steep ramps and other obstacles. The requirement for large angles results in a vehicle with a long wheelbase in relation to its overall length.

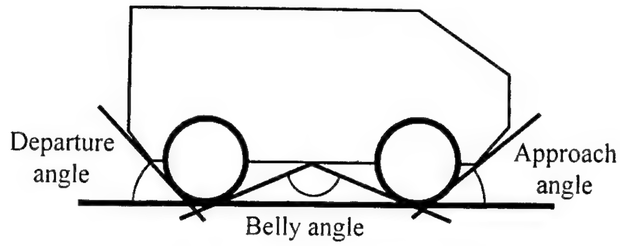


Figure 1-15 Approach, Departure and Belly Angles

In vehicles using tensioned tracks the approach and departure angles are determined by the sprocket and idler locations relative to the front and rear wheelstations. Small approach and departure angles result in sprocket or idler grounding when the vehicle travels at high speed over rough terrain. This adds to crew discomfort and can result in damage to sprockets and idlers. Too large an approach angle can lead to problems in accommodating trailing link front suspension arms and can increase resistance to motion over deep snow.

Belly Angle

An inadequate belly angle (see Figure 1-15) will result in the vehicle "hanging up" when it attempts to cross a ridge, negotiate military bridging or surmount a ramp into an aircraft or landing craft. In two-axle vehicles it is difficult to reconcile large approach and departure angles, which require a long wheelbase, with a small belly angle, which demands a short wheelbase. Belly angle is not a problem for tracked vehicles.

Vulnerability

The location of suspension linkages can expose them to impacts from terrain or to battle damage, which can have a serious effect on terrain accessibility. Some suspension designs are inherently susceptible to these problems.

1.3.2 Types of Suspension System

There are two fundamental types of vehicle suspension system; those in which wheelstations interact with each other and those in which each wheelstation is independently mounted. In the former category are *axles*, in which interaction occurs between wheels on opposite sides of the vehicle, and *bogies*, which incorporate interconnection between axles or between adjacent wheels on each side of the vehicle.

Axles

An axle is essentially a beam connecting two wheels on opposite sides of the vehicle. Therefore these two wheels and the axle move relative to the hull as one subsystem. In a wheeled AFV the axle is usually *live*, that is, it carries within it transmission components which normally include the final drive reduction gears, a differential gear, half shafts and hub reduction gears. If the axle is steered it will also include universal joints.

The axle in an AFV must be of robust construction and this, together with the inclusion of the transmission components, results in a higher unsprung mass than an equivalent independent system. The consequent dynamic problems can be reduced by employing a De Dion axle which is *dead* but still driven. In this design the differential and final drive are mounted on the hull, and drive is transmitted to the hubs via differentially jointed drive shafts. Such a layout is more complex and expensive than a live axle, and is very rarely found in military vehicles, since for a similar amount of investment an independent system could be installed.

Live axles sweep out a relatively large volume under the vehicle, particularly where the bump travel is large. This results in a high floor level and poor packaging (poor use of space), often increasing the height of the vehicle with detrimental effects on stability, step climbing ability and silhouette.

Another problem with live axles is their relatively poor ground clearance, which is determined by the tyre standing radius and the diameter of the differential housing. Ground clearance can be increased by employing a *portal* axle, in which the axle centreline is above the axis of rotation of the wheels. Drive is taken from the half-shafts to the wheels using spur-gears which usually double as hub reduction gears. Whilst the increase in ground clearance is an advantage, the use of portal axles tends to exacerbate the problems of poor packaging, stability and step climbing. For these reasons they are not often used in AFVs, except for vehicles optimised for protection against blast mines in which large open areas under the vehicle are an inherent feature of the mine protection characteristics.

Axles have to be located in such a manner that two degrees of freedom of motion relative to the hull are accommodated under the control of springs and dampers. These are axle bounce (jounce) and roll. The other four degrees of freedom, lateral motion, longitudinal motion, yaw and rotation in pitch, have to be constrained. This is achieved by kinematic linkages, the simplest of which is the leaf spring. This provides an economical, reliable and well developed system which is used in vehicles where high performance is not at a premium. A leaf spring which provides satisfactory location is usually insufficiently compliant to provide a high level of bump travel. This seriously limits vehicle speed on rough terrain.

High performance suspension systems using axles are found in some AFVs but, instead of leaf springs, they employ separate longitudinal links, sometimes supplemented by transverse links, to position the axle. A greater degree of suspension travel is achieved by using coil springs, though hydrogas springs could offer a viable alternative, allowing a softer suspension to be employed with benefits to trafficability and step climbing.

For tracked vehicles the disadvantages of axles outweigh any possible benefits. In AFVs they are found only in those employing wheeled running gear. In multi-axle wheeled vehicles adjacent axles may be interconnected to improve articulation, and hence trafficability on soft terrain. A pair of interconnected axles (a *bogie*) usually involves longitudinal linkages, often resulting in one of the axles being mounted on a leading link. This can increase the effective wheel-rate (see Section 2.1.1) of this axle to the detriment of ride and component dynamic loadings.

Independent Suspension Systems

Independent suspension systems offer the potential for better ground clearance and packaging when compared with those employing axles. This results in a more stable vehicle which can have a smooth belly plate running the length of the vehicle benefitting both trafficability and obstacle crossing.

Modern tracked vehicles use independently mounted wheelstations employing longitudinal links

(wheel arms) to locate the roadwheels, providing a simple compact system which enhances packaging. Normally, trailing links are employed at each wheelstation to reduce the effective wheelrate on rough terrain and hence improve ride. Occasionally, for packaging reasons, leading links may be used on some wheelstations, but for best results the front roadwheels should always be mounted on a trailing link.

Earlier tracked vehicles sometimes used interconnected bogies to improve articulation over rough terrain. In most designs, adjacent pairs of wheels on the same side of the vehicle were interconnected in a manner which resulted in the front wheelstation being mounted on a leading arm. This, together with the fact that the geometry did not facilitate the provision of long wheel arms to allow large suspension travel, resulted in the demise of such systems as AFV cross country speeds increased.

The advantages of the trailing link suspension system can be realised in wheeled AFVs, but there is a major drawback on steered wheels. AFVs need good manoeuvrability which demands large lock-angles in Ackerman steered vehicles. This means that longitudinal wheel arms tend to foul the wheels at full lock. There are examples of trailing links on the steered wheels of an AFV, but the solution involves either short wheel arms, compromising suspension travel, or long cantilevered stub axle assemblies which introduce design difficulties. Therefore, on steered wheels it is normal practice to use transverse link suspension systems.

There are three types of transverse link suspension system in common use:

Swing Axle
This is perhaps the simplest design, involving mounting on the hull the final drive/differential gearbox and pivoting two swinging half axles on it. Due to the relatively small length of the half axle, and the large suspension travel appropriate to an off-road vehicle, the angular movement of each half axle is large, leading to excessive camber change and scrub of the tyres. These introduce handling problems which make this design unsuitable for a high performance vehicle.

Double Transverse Link
The classic design for a transverse link suspension system is the double wishbone layout. This has been used very widely in wheeled AFVs and it offers considerable scope for tuning the suspension characteristics to meet the needs of the vehicle. However the system is complicated and relatively expensive, and the top link intrudes into the hull envelope. If the wheel is steered a useful simplification in design can be achieved if the outer pivots of the upper and lower links lie on the king-pin axis. If ball joints are used at these locations, a separate king-pin assembly is not required.

Strut
This is a very widely used suspension system in automobiles and in recent years it has been employed in some AFVs. In this design the constraint is provided by a lower wishbone and a telescopic strut. This introduces some Coulomb (sliding) friction with its associated wear but, since the normal loads on the sliding surfaces are relatively light, this is not a serious problem. If the axis of the strut is arranged to correspond with the king-pin axis, a particularly simple mechanism results. It offers good packaging.

Transverse link independent suspension systems can be vulnerable. The lower links often lie below the flat bottom of the hull and therefore tend to hook up on the terrain and increase resistance to motion in extreme soft-soil conditions. This type of suspension offers no reduction in effective wheel rate on rough terrain, which can make it more liable to damage when compared with trailing link systems.

Hybrid Systems

Not all suspension systems can be classified as purely transverse or longitudinal link layouts. Some designs use a transverse lower link and a longitudinal upper link, which offers the advantages of a strut type suspension, but with the telescopic sliding mechanism replaced by a short leading or trailing upper link. This removes the Coulomb friction and can be engineered to give favourable kinematic properties.

Another approach would be to use a semi-trailing link design which is popular on rear drive automobiles, offering the simplicity of a trailing link. By using an inclined axis instead of a lateral axis for the inboard pivot, better kinematic properties can be realised. As far as the author is aware such systems have not yet been used in AFVs.

1.3.3 The Influence of Other Components on Terrain Accessibility

Although not strictly under the heading of suspension systems, other running gear components can have a significant effect on terrain accessibility.

Civilian load carriers often utilise dual wheels on the rear axles, but this arrangement is not normally found on wheeled AFVs since it leads to additional hull intrusion. For a given ground pressure, compared to large diameter single wheels, dual wheels increase resistance to motion on soft soils because they leave much wider ruts in the soil. There is some experimental evidence to show that trafficability is more sensitive to wheel diameter than tyre width (see Annex 1C, Section 1C.2.4). Therefore the layout usually adopted for AFVs involves the use of large diameter single wheels with the same track on all axles Large diameter wheels also enhance obstacle crossing capability.

Skid steering, which is usually found on tracked AFVs, can offer outstanding manoeuvrability. However, it can seriously impair mobility in soft soils. When travelling in a straight line both tracks develop equal traction, sufficient in total to overcome the resistance to motion. When skid steering, the traction requirement on the outer track increases and, if trafficability is marginal, the application of steering will reduce the steering effect and can immobilise the vehicle. Similar considerations apply to skid-steered wheeled vehicles.

In an Ackerman steered wheeled vehicle, as in an articulated steer tracked vehicle, both inner and outer wheels (or tracks) normally develop equal traction whilst cornering due to the action of the differentials, thereby maintaining mobility. However, if only the front axles are steered, the vehicle will cut multiple ruts in the soil on corners, which increases resistance to motion. This effect can be minimised by using all-wheel steer but this leads to additional complexity and can introduce handling problems at high speeds on roads. One solution is to lock out the rear steering when operating on highways.

1.3.4 Conclusions

Most of the following conclusions apply to both wheeled and tracked vehicles.

To achieve optimum soft-soil trafficability the weight of an AFV should be spread uniformly over the ground. Theoretically the best way to achieve this is by use of articulation.

Mechanically articulated suspension systems are usually not satisfactory at high speed off-road. Hydraulically articulated systems can be better but are complex. Therefore, multi-wheel running gear with a relatively soft suspension is usually employed in high mobility AFVs.

Soft suspensions in AFVs require a large bump travel, which is also beneficial for step climbing.

Those suspension system architectures which dictate a high vehicle mass centre result in diminished step climbing ability. Suspensions employing axles are therefore at a disadvantage.

A good ground clearance and a smooth unobstructed belly are advantageous for trafficability. This favours independent suspension systems.

Suspension systems with controllable ride height offer benefits in trafficability and, in conjunction with sophisticated control systems, may be used to enhance obstacle crossing.

Skid steering can seriously degrade trafficability. Ackerman steering on wheeled vehicles is better in this respect. All-wheel steer is even more beneficial but not suitable for high speed operation on roads.

1.4 DEVELOPMENTS IN TRACK AND WHEEL DESIGN

Continuing effort is being devoted to improving AFV running gear. Most of this work is focused on improving existing components, but there are a few examples of more innovative activity.

1.4.1 AFV Tracks

Virtually all tracked AFVs employ link tracks, and they are used exclusively in vehicles within the weight range of interest to this report. Continuous band tracks have been used in very light vehicles and are currently being trialled in vehicles at the bottom end of the 10-25 US ton range.

Link Tracks

Major problems with conventional link tracks are the maintenance burden, the cost and frequency of replacement, and their considerable weight. There are also concerns regarding the energy dissipated in the track which reduces performance, increases fuel consumption, and adds to thermal signature. Limitation of road speed due to concerns over track integrity is also a disadvantage.

Manufacturers are constantly striving to reduce the weight of tracks. This will reduce the combat weight of a vehicle with benefits to ground pressure and performance. In recent years there has been a trend to fit double-pin rubber-bushed tracks in place of single dry-pin tracks, particularly to heavy AFVs, in the search for higher track mileage and hence reduced cost. This has entailed the penalty of increased weight. Lightweight materials, such as aluminium alloys, have been tried with limited success so far but there may be scope for further development.

For vehicles in the 10-25 US ton range, single-pin track is adequate. This tends to be lighter and cheaper than double-pin track. Most vehicles use rubber-bushed links, which offer a much longer life than dry-pin track. Attention to detail design of the bushes has resulted in useful reductions in track losses with benefits to mobility. Single-pin track links tend to be more aggressive than double-pin designs, which enhances trafficability on wet cohesive soils. Further development of double-pin designs is likely in this respect.

With careful design and some compromises, it appears that steel double-pin track can be brought down to a similar weight to single-pin track for light AFVs. A significant contribution to this has been the adoption of sprocket drive to the body of the track link rather than to the end connectors. Whilst this entails wear on the body, which now becomes a throw-away item, it allows a reduction in the size of the track pins and bushes with a consequent reduction in weight.

Some work has been done on applying modern unlubricated bearing technology and sealed bearing cartridges to "dry" pin track in an attempt to reduce the friction losses and wear (see [1.8]). If successful, this would combine the lightness of single dry-pin track with the life of rubber-bushed track. The results so far have not been promising but there may be future potential as improved "dry" bearing materials are developed.

Continuous Band Tracks

A number of manufacturers offer continuous band tracks for off-road vehicles. Some of these are being trialled on AFVs. Clearly they are at present only suitable for light vehicles at the bottom end of the range of interest. They offer a number of advantages including light weight, low acoustic signature, much lower levels of track-induced vibration and the potential for higher road speed. It was hoped that such tracks would incur lower energy dissipation but, in trials, this has not been realised (see [1.9]). A long track life is claimed with much reduced track costs. There are serious concerns about vulnerability to damage from enemy action and terrain. Moreover, it is

not practicable for the crew to perform a track change in the field, even if a spare track could be accommodated. However, emergency repair kits have been developed to provide a temporary joint in a severed track. The track is not as aggressive as steel track, which can result in reduced trafficabilty on clays. Despite these drawbacks, there is serious interest in persevering with the concept.

Other Tracked AFV Running Gear Components

In an effort to save weight, experiments have been carried out with non-metallic roadwheels for tracked AFVs. Various materials have been tried but with limited success to date. There are serious problems arising from the high temperatures to which these components are subjected as a result of energy dissipation from the solid rubber tyres. Exotic temperature resistant materials involve high cost.

Trafficability improvements can be achieved by increasing track tension on marginal terrain. However the levels of tension involved would result in reduced life and reliability at high speeds, particularly on roads. Some work has been done on variable track tension systems, particularly in Scandinavia, with a view to enhancing trafficability on snow (see [1.10]). This is a very promising approach but suitable monitoring and, perhaps, intelligent control systems are desirable to prevent damage.

1.4.2 AFV Wheels and Tyres

The benefits of CTIS for wheeled AFVs are now widely appreciated and most AFV manufacturers either fit CTIS as standard equipment or offer it as an option. The technology is, of course, not new but reliability and control strategies have improved.

Most wheeled AFVs, in the 10-25 US ton range, use radial-ply tyres with general purpose on/off-road treads. These are readily available at acceptable cost and offer a reasonably low rolling resistance coefficient and low wear rate. Their flexible sidewalls are compatible with CTIS and with run-flat systems based on some form of inner wheel. However, these tyres are relatively vulnerable to sidewall damage which, on some types of terrain, results in frequent punctures.

In response to this problem a range of non-pneumatic tyres has been developed in Australia. One type uses a modular approach in which a series of chevron shaped hollow rectangular tread elements is bolted to a fabricated steel wheel. Since it does not rely on air under pressure it is totally puncture proof. Damaged segments of the tread can be replaced individually from a stock carried on the vehicle. The system is understood to work very well off-road but it is not suitable for continuous high speed operation on highways. The current product is only suitable for vehicles of mass less than 5 tons or so.

A prototype solid-tyred wheel has been designed to permit higher road speeds than the modular system, but is much heavier than an equivalent pneumatic tyre and cannot operate at such high speeds. However it is totally puncture proof and again limited to light vehicles.

The normal approach to reducing the consequences of punctures is to use some form of run-flat system. There are several well developed commercial systems available, most of which employ some form of inner wheel. These come with a variety of levels of resilience and offer various degrees of mobility following a puncture. There are, however, penalties in terms of weight, cost and logistic implications.

There have been proposals, and some development work, concerning various types of deformable wheel for off-road vehicles. In some designs the wheel adopts a roughly elliptical shape under load which gives an elongated contact patch with consequent reduction in ground pressure. In

other designs the spokes of the wheel are resilient, thus providing suspension. None of these ideas has so far proved appropriate for wheeled AFVs.

1.4.3 Other Components

The benefits of suspensions which allow control of vehicle ride height have already been mentioned. The ability to increase ground clearance can be a valuable aid to soft-soil trafficability and obstacle crossing. Control of the suspension preload on each axle individually allows adjustment of pitch angle and can further assist step climbing. Whilst this technology is not new it is not widely employed.

In tracked vehicles travelling at high speed on rough terrain there can be a high incidence of front sprocket/idler grounding. This can result in damage to the vehicle and injury to the crew, and may limit cross-country speed. A prototype vehicle has been fitted with a sprung front idler using hydrogas technology. This results in a useful improvement, and allows the vehicle to negotiate obstacles at considerably higher speeds.

Virtually all wheeled AFVs have some form of traction control system. There are many competing strategies ranging from differential locks and selectable all-wheel drive mechanisms to fully automatic systems which require no driver intervention. These can provide significant improvements in trafficability. The use of the more sophisticated mechanically-based systems will probably increase in the short term. In the longer term, reliable, efficient and compact electric transmission systems may emerge incorporating fully electrical traction control on individual wheelstations.

1.4.4 Conclusions

There do not appear to be any revolutionary technical advances on the horizon which will transform the terrain accessibility of AFVs in the weight range 10-25 US ton.

Steady development of existing technology will continue to offer improvements in the short term. This may well include the wider adoption of variable ride height and track tension systems.
In the longer term, continuous band tracks may become more competitive with link tracks and, providing vulnerability issues can be resolved, may be used in tracked AFVs.

A wider adoption of automatic traction control systems in wheeled AFVs is likely in the short term, enabling the full trafficability potential of current wheeled vehicles to be achieved.

In the longer term, developments in electric transmission technology, with individual wheel torque management on wheeled vehicles, may reach the stage where they are viable for AFVs.

REFERENCES FOR SECTION 1

1.1 Hall L C "A comparison of various methods of quantifying soft soil mobility of AFVs" Report No RMCS/ESD/LCH/175/99 Royal Military College of Science, Shrivenham, UK Sept 1999

1.2 Janes "Armour and artillery" 19th edition 1998-99

1.3 Maclaurin E B "Proposed revisions to MMP based on the results of tractive performance trials with single pneumatic tyres and a modular track system" Report No DERA/LS4/TR970122/1.0 DERA Chertsey 1997

1.4 Maclaurin E B "The tractive performance of wheeled vehicles in sand" Division Note No MS4/04/90 RARDE Chertsey 1990

1.5 Wong J Y "Application of the computer simulation model NTVPM-86 to the development of a new version of the IFV ASCOD" Journal of Terramechanics Vol 32 No 1 1995

1.6 Hohl G and Peschak B "A computer aided method for the prediction of the obstacle crossing ability of two-axle wheeled vehicles" Wheels and Tracks Symposium 9-11 September 1988 RMCS Shrivenham

1.7 Moore N and Laughton B R "Validation of a computer based obstacle crossing simulation model for tracked vehicles" 22 ASC Advanced Study Report Royal Military College of Science, Shrivenham, UK Nov 1987

1.8 Macdonald W J J "Interim report on a cost effective and durable AFV track" Memorandum 83019 MVEE Chertsey Dec 1983

1.9 Maclaurin E B "An investigation into the potential of continuous flexible rubber tracks for light AFVs" Report No DERA/LS4/CR980221/1.0, DERA Chertsey 1998

1.10 Falk A "Mobility improvements in tracked vehicles" Proceedings of the 2nd European AFV Symposium 27-29 May 1997 RMCS Shrivenham

LIST OF ABBREVIATIONS

AFV	Armoured fighting vehicle
APSG	Average pressure on soft ground
CBR	California Bearing Ratio
CI	Cone index
CI_L	Limiting cone index
CTIS	Central tyre inflation system
DBP	Drawbar pull
DERA	Defence Evaluation and Research Agency
GVW	Gross vehicle weight
IFV	Infantry fighting vehicle
MBT	Main battle tank
MI	Mobility index
MMP	Mean maximum pressure
MRAV	Multi Role Armoured Vehicle
NATO	North Atlantic Treaty Organisation
NGP	Nominal ground pressure
NRMM	NATO Reference Mobility Model
R&H	Rowland and Harding
RCI	Rating cone index
RMCS	Royal Military College of Science
VCI	Vehicle cone index
VLCI	Vehicle limiting cone index
WES	Waterways Experimental Station, US Army Corps of Engineers

ANNEX 1A NATURE AND PROPERTIES OF SOIL

1A.1 STRUCTURE OF SOIL

All soils consist of particles and the voids between these particles. The voids may be filled with water or some air and some water. The properties of the soil depend on the nature of the particles (which will be discussed below) which is constant for a particular soil, and on the size and contents of the voids. The latter frequently change, thereby greatly changing the soil properties. For example, a soil which has recently been ploughed will have much larger voids than one which has been undisturbed. The amount of water in the soil will also vary widely between winter and summer, or between dry and wet seasons, and indeed after every shower of rain. Thus it is only possible to determine properties such as strength of a soil in a given condition.

The general condition of a soil can be indicated by its unit weight, symbol γ (often loosely and incorrectly called its density). It can be expressed as the *bulk unit weight* γ, i.e. the total weight of unit volume, or as the *dry unit weight* (γ_{DRY}), the weight of dry matter in unit volume of the soil in its existing state (i.e. not when dried).

The extent of the voids in the soil can be expressed as the *void ratio*, symbol e, defined as the ratio of the volume of the voids to the volume of the solid matter, or as the *porosity*, symbol n, defined as the ratio of the volume of the voids to the total volume of the soil.

The amount of water in the soil is always expressed as the *moisture content*, symbol m, defined as the weight of water in unit weight of dry matter, usually expressed as a percentage. If the voids are completely filled with water, the soil is described as *saturated.*

The solid matter consists of mineral particles, varying in size from sub-microscopic to pebbles, and of organic matter. The latter is largely ignored in normal soil mechanics activities but is of importance in vehicle mobility work. Its presence always reduces the strength of a soil, both because the organic particles are themselves weak and because they retain an open structure and hence a high void ratio and also a high moisture content. Where the proportion of organic matter exceeds about 20 %, the soil is described as *organic* (eg. peat, muskeg). This is always very weak, but it is often assumed (without much convincing experimental evidence) that it obeys similar strength laws as conventional "civil engineering" soils.

1A.2 SOIL PARTICLES

Soils, other than organic soils, are classified and named according to the size of the predominant particles they contain. The most common types of soil are listed below with their predominant particle sizes:

Clay	Sub-microscopic, feels plastic (< 0.002 mm)
Silt	Grain visible under a microscope - feels soft (0.002 - 0.06 mm)
Sand	Feels gritty (0.06 - 2 mm)
Gravel	Looks like gravel (> 2 mm)

In terramechanics soils are classified as:

Fine grained soils, usually called "clay" but including silt (< 0.06 mm)

Coarse grained soils, usually called "sand" but including gravel (> 0.06 mm)

Many soils are, of course, a mixture of both, but can be put arbitrarily into one or the other of these categories according to whether more or less than 35% will go through a 60 μm sieve. A silt or clay content of more than 35% makes a soil behave as a fine grained soil.

1A.3 SOIL STRENGTH

Soil has little or no tensile strength but is very strong in direct compression. Its mode of failure is almost always in shear, so this is the stress and strength which are of greatest interest.

The shear strength of many soils includes an element of friction, and therefore depends on the stress normal to the plane of failure. The shear stress is given by the formula:

$$\tau_f = c + \sigma_n \tan\phi$$

where τ_f is the shear stress at failure (i.e. the shear strength), σ_n is the normal stress across the failure plane and c and ϕ are soil properties. The first of these, c, is known as the *cohesion* and ϕ is the angle of shearing resistance of the soil (i.e. the angle of "internal friction")

A dry sand has no cohesion and hence $c = 0$. It is purely frictional so $\tau_f = \sigma_n \tan\phi$, where ϕ, typically, might be in the range 30 - 36°.

More often than not, clays are saturated (certainly in the UK). If a normal stress is applied to a saturated clay the water that fills the voids, being relatively incompressible, carries the load, none of which goes on the solid particles. The passages formed by the voids are so small that it takes a long time for the water to be squeezed out. In civil engineering work this will happen over a year or two. Vehicles do not usually stay in one place for very long and therefore the normal load applied by a vehicle makes no difference to the soil strength (water of course has no shear strength), hence $\phi = 0$ and c may lie in the range 20 to 100 kN/m^2.

Many ordinary soils have both cohesive and frictional properties, but in practice it is found that where there is a small percentage of clay present the frictional effects are small compared to the effects of cohesion, and hence they behave essentially as clays.

1A.4 MEASUREMENT OF SOIL STRENGTH PROPERTIES

1A.4.1 Cone Index (CI)

This is the most widely used method for measuring the strength of soils in terramechanics. It is determined using a *cone penetrometer*, an easily portable instrument which measures the force required to push a steel cone of projected area 0.5 in^2 into the soil by hand. Although the results obtained only give an approximate measure of the trafficability properties of the soil, which involve several different parameters requiring laboratory determination, the speed and convenience of the measurement makes it extremely attractive.

For civil engineering work larger cones are sometimes used which are driven into the soil by hydraulic rams.

Experience shows that in clay soils of uniform consistency the cone index does not vary significantly with depth of penetration over the range of depths of interest in terramechanics. The average value of the cone index over the top 150-200 mm of the soil is normally quoted as a measure of the strength of the soil. Clearly if the consistency changes with depth, for example in a field ploughed to a particular depth, cone index will increase as the penetrometer reaches that depth.

1A.4.2 Remoulding Index (RI)

Many silt, clay and organic soils lose strength when they are disturbed from their natural condition. Therefore the strength, except under the leading wheels of a vehicle, may be less than that indicated by a cone penetrometer. This can be allowed for by the introduction of a *remoulding index.* Unfortunately this is much more difficult to measure than the CI and is usually estimated in the field. Typical values are unity for course grained soils, 0.8 for inorganic clays, 0.4 - 0.6 for very silty or organic soils and 0.2 for peat.

1A.4.3 Rating Cone Index (RCI)

This is the product of cone index and remoulding index and is the value normally used in vehicle mobility calculations.

1A.4.4 Penetration Resistance Gradient

In sandy soils it is found that the reading of a cone penetrometer increases approximately linearly with depth of penetration over the range of depths of interest in terramechanics. The gradient of the graph of cone index against depth is called the *penetration resistance gradient* and is an important measure of the strength of the sand.

1A.4.5 California Bearing Ratio (CBR)

This is another empirical measure of soil strength used in civil engineering applications. In this measurement the penetration resistance of a blunt rectangular plunger having an area of 3 in^2 is determined. This method is used for assessing the suitability of soils for the foundations of roads and buildings, but is not usually used in terramechanics.

1A.4.6 The Bevameter

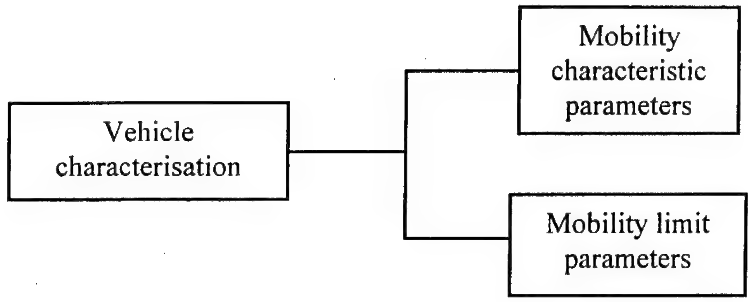
This device was originally conceived by Dr M G Bekker who argued that since a vehicle applies both normal and shear stresses to the soil, the strength of the soil in response to normal and shear forces should be measured. He developed the *Bevameter* which measures pressure-sinkage data from a loaded circular plate and shear stress-displacement data developed by a loaded annular ring. From these data values of two parameters, K_c and K_ϕ, relating to cohesion and friction respectively, are determined. These are used in his theoretical techniques for predicting mobility (see Annex 1B section B2.2.3) The measuring equipment is much larger than a cone penetrometer and is sometimes vehicle mounted.

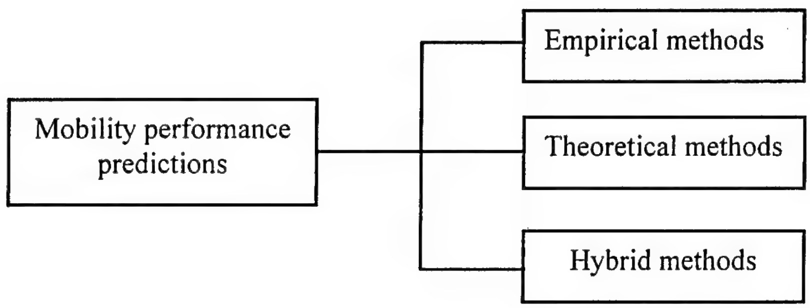
1A.4.7 Triaxial Test

This is a laboratory test for measuring a range of soil properties, particularly c and ϕ. Determination of soil strength by this method forms the basis for all civil engineering soil mechanics investigations and is particularly appropriate for deep foundation work where the soil is loaded laterally by "hydrostatic" forces as well as vertically by the load it carries. It is clearly a less convenient method than the others but gives a more complete description of the characteristics of the soil. A version of the triaxial test, known as the *unconfined compression test*, has been developed for use in the field, but it is little used and only works for fine-grained soil.

ANNEX 1B METHODS OF QUANTIFYING SOFT-SOIL TRAFFICABILITY

An extensive literature survey was carried out which revealed a large number of different ways of quantifying mobility. The overall picture is potentially very confusing and so these methods were classified under several headings as follows:





1B.1 VEHICLE CHARACTERISATION

In this approach the mobility of a vehicle is described by quoting the value of a single parameter which quantifies soft-ground mobility and is characteristic of the vehicle. Several different parameters have been developed to achieve this. They can be grouped under two headings, *mobility characteristic parameters* and *mobility limit parameters.*

Mobility characteristic parameters depend only on the vehicle specification and make no reference to the type of soil on which it operates. Their utility is restricted to facilitating comparisons between different vehicles since they are not designed to make any sort of prediction of the type of soils which the vehicle can overcome.

Mobility limit parameters on the other hand are designed to indicate the minimum strength of soil on which the vehicle can be expected to remain mobile. This parameter is potentially more useful in the field, particularly where soil conditions are known from going maps or from measurements.

1B.1.1 MOBILITY CHARACTERISTIC PARAMETERS (Tracked vehicles)

1B.1.1.1 Nominal Ground Pressure (NGP_T)

This is the oldest method of characterising the mobility of tracked vehicles and it is still widely used. It is, as its name implies, a measure of the average pressure exerted by the track on the ground and is calculated by dividing the weight of the vehicle by the projected area of its tracks in contact with the ground (see Annex 1C1.1). This provides a broad measure of the relative capabilities of tracked vehicles having similar running gear architecture, but can be misleading when comparing tracked vehicles having significantly different running gear layouts. It is too

favourable to tracked vehicles to serve as a basis for meaningful comparisons with the capabilities of wheeled vehicles.

One of the difficulties with using NGP is concerned with defining the projected area of the tracks in contact with the ground. At one extreme the product of the overall width of the track and the length of track in contact with the ground (including those parts ahead of the front roadwheel axis and behind the rear roadwheel axis due to sinkage) could be used. Usually the length of track in contact is assumed to be the distance between front and rear roadwheel axes. The product of this and the track width gives the *nominal contact area* which can be further modified by a factor which takes account of the ratio of the projected area of each track link to the product of track pitch and overall width. At the other extreme the total area of the track pads could be used, which obviously gives higher values of NGP and is only appropriate in circumstances where sinkage is minimal. Care must be taken to ensure that the area used is consistent when comparing NGPs of different vehicles.

1B 1.1.2 Mobility Index (MI_T)

This parameter was developed by the Waterways Experimental Station (WES) of the US Army Corps of Engineers. It was derived from the work done on the VCI_T parameter (see section 1B.1.3.2). Having established the VCI of a number of tracked vehicles by experiment, empirical methods were used to correlate these results with the characteristics of the vehicle running gear by combining them into a single parameter which was called the *Mobility Index* (see Annex 1C.1.2). Unfortunately the mobility index formula which emerged is dimensionally inconsistent and contains arbitrary factors which are not strictly relevant to the terramechanics of the problem. This fact undermines the scientific credibility of this parameter.

1B 1.1.3 Mean Maximum Pressure (MMP_T)

This parameter arose out of the inadequacies of NGP as a means of assessing mobility. It was realised that sinkage, and hence rolling resistance, depends not merely on the average pressure exerted by the vehicle on the ground but is related to the peak pressures experienced by the terrain. The distribution of ground pressure along the length of the track is very variable, peaking under the roadwheels (see Figure 1B1). These peak pressures can be two to four times the average value. Hence it is not surprising that different degrees of sinkage have been observed with vehicles of similar NGP but different running gear configuration.

Rowland [1B1], at the Fighting Vehicles Research and Development Establishment (now DERA Chertsey), measured the variation of ground pressure under the tracks of a variety of vehicles on different cohesive soils and demonstrated that sinkage is related to the average of the peak pressures at the track/soil interface. He defined this average as the MMP and correlated it with the design parameters of the running gear (see Annex 1C.1.3).

MMP was recognised in the UK as a superior parameter to NGP and is used both as a design tool and as a way of comparing the relative merits of different tracked vehicles. Its limitations include the fact that it takes no account of track tension, which tends to reduce the pressure peaks under the front and rear roadwheels and to smooth out variations between the others. It is not suitable for vehicles fitted with continuous band tracks. Wong [1B2] argues vigorously that the fact that it takes no account of the properties of the terrain undermines its credibility in predicting the peak pressures under the track and hence the sinkage and the mobility of the vehicle.

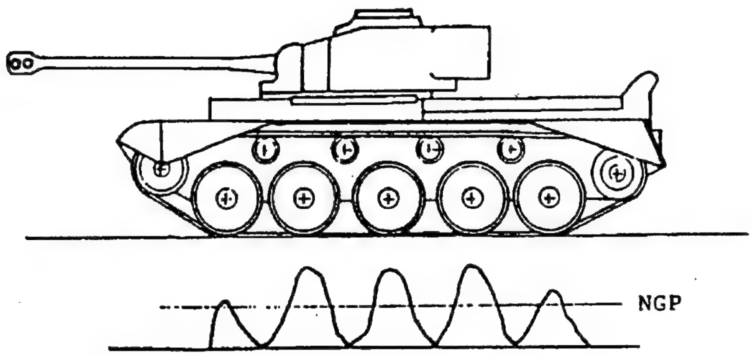


Figure 1B1 Pressure Variation Under Tracked Vehicle

Despite these criticisms MMP offers a simple, logical and reasonably credible method of quantifying the mobility characteristics of a tracked vehicle employing conventional linked tracks operating on cohesive clay soils. It is assumed that comparisons made on this basis are valid for other types of soil, but this has not been widely verified. There is evidence that on dry sand the MMP correlates very inadequately with the measured average of the peak pressures under a track [1B3].

1B.1.2 MOBILITY CHARACTERISTIC PARAMETERS (Wheeled vehicles)

1B.1.2.1 Nominal Ground Pressure (NGP_W)

The basic concept of NGP for wheeled vehicles fitted with pneumatic tyres is identical to that for tracked vehicles (see section 1B.1.1.1) but the problem of defining the contact area between the vehicle and the ground is more acute, since in practice the actual contact area varies greatly with sinkage and, to a lesser extent, with inflation pressure. It is usual to assume that the width of the contact area of a tyre is equal to its section width and that the length of the contact area equals the undeflected radius of the tyre (see Annex 1C.2.1). This corresponds to a sinkage of approximately 6% of tyre diameter. It will be immediately apparent that this level of sinkage is chosen somewhat arbitrarily. Therefore, whilst comparisons of the NGPs of different wheeled vehicles may be reasonably satisfactory, this parameter should not be used to compare wheeled and tracked vehicles, or wheeled vehicles fitted with CTIS and those using tyres inflated to road pressures.

1B.1.2.2 Average Pressure on Soft Ground ($APSG_W$)

This is a European equivalent of NGP for wheeled vehicles, but based on a sinkage of 75 mm (see Annex 1C.2.2) and an assumption that the shape of the tyre is the same as that on a hard pavement. Unlike NGP, this parameter includes an allowance for the effect of tyre inflation pressure.

1B 1.2.3 Mobility Index (MI_W)

This parameter was developed by the Waterways Experimental Station (WES) of the US Army Corps of Engineers. It was derived from the work done on the VCI_W parameter (see section 1B.1.4.2). The methods employed were identical to those used for tracked vehicles (see section 1B.1.1.2) and the mobility index formula which emerged (see Annex 1C.2.3) suffers from the same drawbacks as that for tracked vehicles. A close examination of the formula reveals that MI

is much more sensitive to changes in tyre section width than to diameter. This is contrary to their influence on MMP and on mobility predictions based on mobility numerics.

It should be noted that the WES validation trials were carried out on wheeled vehicles whose weight was less than 10 tonne. Extrapolation of this approach to heavier vehicles should be treated with caution.

1B.1.2.4 Mean Maximum Pressure (MMP_W)

Rowland Formula

Unfortunately Rowland did not extend the scope of his measurements of the peak ground pressures imposed by vehicles to those having wheeled running gear. Instead he attempted to derive for them an "equivalent MMP" [1B4]. His intention was to produce a unifying parameter equally valid for wheeled and tracked vehicles. He based his work on an empirical relationship derived from traction tests of pneumatic tyres on heavy clay cohesive soils in laboratory soil bins carried out by WES and on values of VCI of a number of tracked vehicles also determined by WES. By correlating these two sets of data he proposed an equation for the MMP of wheeled vehicles (see Annex 1C.2.4).

This parameter is only valid for wet cohesive soils of the kind associated with agricultural terrain. The WES tests were not carried out on the type of large tyres carrying heavy loads which are used on modern AFVs and only very limited field testing was undertaken to validate the predictions. Some of the values for the constant K (see Annex 1C.2.4) were based on very limited data, however the underlying structure of the formula is founded on the mobility numerics approach described in section 1B.2.1.1. The MMP_W formula was not verified experimentally, in the same way as MMP_T, and the indirect route followed in its derivation undermines its credibility, particularly when used for large heavily loaded tyres.

It should be noted that, despite its name, MMP_W is not intended to be used to predict the average of the peak pressures imposed on terrain by the wheels of a vehicle. Experiments using buried pressure transducers have shown that measured values of peak pressures can significantly exceed those indicated by MMP_W [1B5].

MMP_W has come to be accepted as a useful tool for comparing the mobility of different wheeled vehicles on clay but there are serious doubts regarding its validity in comparing wheeled vehicles with those using tracked running gear. A later development incorporated factors to accommodate the improved mobility offered by the use of differential locks. The factors used appear to be notional and detract from the fundamental terramechanics basis of this method, since the engagement of differential locks, whilst undoubtedly improving traction control, does not fundamentally decrease ground pressure.

One of the practical difficulties in using the MMP equation given in Annex 1C.2.4 lies in the definition of the tyre section height. This is the height from the lip of the rim of the wheel to the bottom of the tread. This cannot be obtained easily from tyre catalogues, and it is more usual to regard the section height as half of the difference between the tyre and wheel diameters. This opens up the possibility of confusion which can have a significant effect on the MMP value.

Maclaurin Formula

The inadequacies of the Rowland formula for wheeled vehicles have long been recognised. At DERA Chertsey an experimental rig was constructed which was capable of measuring the traction and rolling resistance characteristics of both a single wheel and a track assembly using the same measuring equipment over substantially the same terrain. A number of experiments have been

carried out using a range of different tyres and track arrangements on cohesive soils, and the results have been analysed using mobility numeric methods (see section 1B.2.1.1). These results revealed that there was very little difference in the mobility of a single wheel between the first and subsequent passes in the same rut under the same conditions of load and inflation pressure. However, in these experiments there was, of necessity, a long time delay between successive passes, unlike the situation presented by a multi-axle vehicle.

From this data a formula for MMP for wheeled vehicles was proposed for all-wheel drive vehicles of approximately uniform weight distribution (see Annex 1C.2.4) which was claimed to offer a better correlation with that of tracked vehicles. This formula has not been published in the open literature but was incorporated in the Statement of Requirement for the Multi-Role Armoured Vehicle programme.

One feature of this formula is the use of δ/d instead of δ/h to include the effect of tyre inflation pressure (see Annex 1C.2.4). This is claimed to be more fundamental to the influence of the tyre on the displacement of the soil, to reduce the number of terms in the equation, to give a slightly better correlation with experimental data and to be more consistent when applied to high and low profile tyres. Since it does not include the tyre section height it also removes the problem of confusion in the definition of that parameter.

This approach looks very promising and offers a credible way of solving the problem of providing a unifying parameter for characterising the mobility of wheeled and tracked vehicles. Due to the random errors associated with measurements in terramechanics, a large body of data must be collected before reliable conclusions can be drawn. Regrettably, despite its obvious importance, this programme of work did not attract funding and hence such a body of data is not available, and will probably not be collected in the future.

The predictions of the new formula are considerably more favourable to wheeled vehicles than those of the Rowland formula and have been received with some scepticism in certain quarters. One limitation of the work is the fact that the experimental results were collected from single wheels, rather than from multi-wheel vehicles which impose repetitive loading. Additionally the DERA rig was only big enough to accept track systems from light AFVs, and extrapolating the results to heavier vehicles may introduce some errors.

1B.1.3 MOBILITY LIMIT PARAMETERS (Tracked vehicles)

1B.1.3.1 Limiting Cone Index (CI_L)

Rowland tried to correlate his MMP values with the actual mobility capabilities of tracked vehicles measured in terms of the minimum soil cone index on which they could operate in a single pass. Using data from trafficability tests carried out in the USA he discovered that this was roughly proportional to MMP and he therefore defined a limiting cone index which is calculated by multiplying the MMP by a constant (see Annex 1C.3.1). This, like MMP, is valid only for clay soils.

1B.1.3.2 Vehicle Cone Index (VCI_T)

A large number of trials was carried out by the Waterways Experiment Station (WES) [1B6] to establish the mobility limits of a range of tracked vehicles. On the basis of numerous trafficability tests each of these vehicles was awarded a VCI value corresponding to the cone index of the softest terrain which it could traverse. Measurements were limited to wet fine-grained cohesive soils. This procedure is extremely costly and laborious and therefore a method for predicting VCI_T was developed using the mobility index parameter described in section 1B.1.1.2. The

concept is, in principle, very sound, as the vehicle mobility parameter is directly related to the measured capability of the vehicle. When the VCI is derived directly by experiment the system should be reliable within the limits of the cone index approach to the measurement of soil strength (see section 1A.4.1). This approach can obviously only be used for existing vehicles rather than for assessing design proposals. For this type of work values of VCI_T have to be estimated using the empirical MI_T approach (see section 1B.1.1.2). Predictions based on MI_T should be treated with some caution.

1B.1.3.3 Vehicle Limiting Cone Index ($VLCI_T$)

This parameter was proposed by Maclaurin [1B7] following a series of trials using the mobility test rig described in section 1B.1.2.4(b) to compare the mobility characteristics of wheels and tracks. The parameter, which is defined in Annex 1C.3.3, indicates the minimum cone index of a fine grained soil on which the vehicle can be expected to remain mobile.

1B.1.4 MOBILITY LIMIT PARAMETERS (Wheeled vehicles)

1B.1.4.1 Limiting Cone Index (CI_L)

This parameter is similar to that for tracked vehicles and is similarly determined from the MMP. As has already been noted the MMP_W formula was not based on direct measurement of ground pressure but derived indirectly, and hence CI_L will reflect this (see Annex 1C.4.1).

1B.1.4.2 Vehicle Cone Index (VCI_W)

This parameter was developed in exactly the same way as that for tracked vehicles (see section 1B.1.3.2) and therefore has the same advantages and disadvantages. It should be noted that MI_W is not influenced by tyre inflation pressure even though this has a very significant effect on mobility. Early empirical equations for estimating VCI_W from mobility index ignored this fact but a later correction (which is embodied in NRRM II) included a tyre static deflection term (see Annex 1C.4.2). As has been noted previously, extensive validation has not been carried out on vehicles of the weight class of interest in this study.

1B.1.4.3 Vehicle Limiting Cone Index ($VLCI_W$)

This is the equivalent parameter to $VLCI_T$ for wheeled vehicles and is described in the same reference (see section 1B.1.3.3 above). It should be noted that the formula (see Annex 1C.4.3) is based on the results of a series of trials on single wheels, and therefore the use of this formula to predict the mobility limits of a multi-wheeled vehicle may introduce errors. Further experimental validation is clearly desirable.

1B.2 MOBILITY PERFORMANCE PREDICTIONS

These are more elaborate ways of predicting vehicle mobility. They are designed to predict the performance of vehicles on different types of soil in terms of the rolling resistance, gross traction and net traction (or drawbar pull), often as a function of longitudinal slip. The methods used can be *empirical*, achieved by fitting equations to the results of experimental investigations, or *theoretical*, based on the application of fundamental mechanics to off-road locomotion. There are, in addition, *hybrid* methods which rely on a combination of empirical and theoretical methods. The more complex theoretical methods are usually implemented using digital computer programs.

1B.2.1 EMPIRICAL METHODS

1B.2.1.1 Mobility numerics

This is an empirically based method of interpolation of the large body of experimental results obtained by WES and other researchers. The original experimentation was carried out by WES on single tyres of various sizes running in laboratory soil bins containing a wet, highly plastic clay soil.

The approach relies on deriving non-dimensional mobility numbers to reduce the number of variables and using regression techniques to achieve the best fit between these and the experimental data. The mobility numbers reflect a relationship between running gear characteristics and soil strength. A variety of equations have been proposed over the years, which have been verified by conducting trials in laboratory soil bins or on real vehicles. The WES trials revealed that the laboratory data predicted higher performance than that achieved in the field, but gave results of similar form.

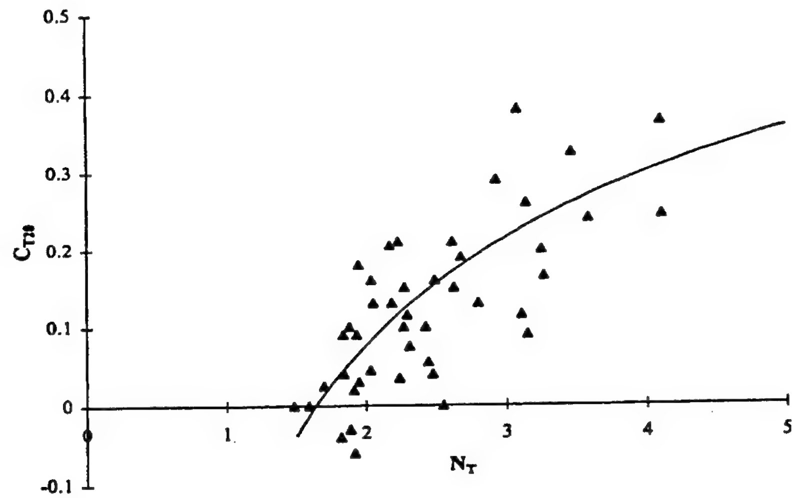


Figure 1B2 Typical Experimental Mobility Data

The soil properties are usually based on cone penetrometer readings which, as has been noted, give only an approximate indication of the strength of the soil. It is not surprising therefore that the fitted equations are effectively the average of a highly variable set of data (see Figure 1B2) and therefore the method is not particularly accurate when attempting to predict performance over a specific piece of terrain. It however is quite valuable when comparing the capabilities of different vehicles.

Using mobility numerics, predictions can be made of rolling resistance, gross traction and drawbar pull, as a function of longitudinal slip and terrain cone index. It can be used to determine the limiting cone index which a vehicle can be expected to cope with.

Mobility numerics have been developed by a number of researchers for both wheeled and tracked vehicles in both clay and sand. Although the original numerics system, developed at WES, did not cover the important case of tracks on clay, later work by Rowland proposed an equivalent mobility number derived from MMP_T and RCI (see Annex 1C.5.1).

The clay mobility numbers have been more widely verified than those for sand and, within the usual limits of accuracy associated with terramechanics, can give good results. For sand the position is not so clear cut due to the inadequacy of the penetration resistance gradient in quantifying the properties of different types of sand with different moisture contents.

1B.2.1.2 Excess Soil Strength

This method is used in the NRMM II for predicting drawbar pull on fine-grained soils. It involves calculation of the *excess soil strength*, which is found by subtracting the vehicle cone index from the rating cone index of the soil. This value is then substituted in suitable empirical equations to determine the drawbar pull coefficient. Clearly the vehicle will become immobilised on level ground when the excess soil strength is zero, i.e. the RCI of the soil equals the VCI. This method relies on accurate determination of the VCI and reliable empirical equations.

1B.2.2 THEORETICAL METHODS

1B.2.2.1 Micklethwait's Theory

Micklethwait proposed a relationship for predicting the maximum possible gross traction which could be developed by a vehicle. It was based on the sum of the traction available from the cohesive strength of the soil and that available from friction at the vehicle-soil interface.

1B.2.2.2 British Theory for Clay

Early theoretical methods were based on deriving expressions for the work done in compressing the soil under rigid wheels or tracks. Simple pressure-sinkage relationships were invoked to make predictions of the rolling resistance. When combined with Micklethwait's theory a method for predicting mobility characteristics was developed. These methods give approximate estimates of mobility for smooth solid wheels on clay but do not take account of soil displacement which strongly affects the behaviour of real vehicles.

1B.2.2.3 Bekker's Method

This is the result of a pioneering theoretical study of tracked vehicle mobility which modelled the variation of pressure under the wheels and the resulting sinkage [1B8]. The effects of vehicle weight, track width, roadwheel spacing and the pressure-sinkage relationship of the terrain were taken into account. The study was limited to the analysis of the shape of the track between two roadwheels, simplified as knife-edge supports, in a terrain with a linear pressure-sinkage relationship.

This approach relies on soil data gathered experimentally using the Bevameter (see Annex 1A, section 1A.4.6) which are used to predict a pressure-sinkage relationship which is employed in the theoretical analysis. The resulting relationship is dimensionally curious and the analysis is more laborious than the simple approach without delivering any better accuracy.

1B.2.2.4 Reece's Equation

Dr Reece at Newcastle University produced a much more satisfactory pressure-sinkage relationship which enabled him to develop Bekker's method further. Though more successful than Bekker's approach it has not been validated to the extent that it can be relied upon to make reliable predictions under field conditions.

1B.2.2.5 The Wong Computer Model

Dr Wong and his colleagues at Carlton University have put a great deal of effort into the development of a complex computer based analysis of the mechanics of a tracked vehicle travelling over soft terrain. This is claimed to give accurate predictions of vehicle performance but the program is elaborate and requires a great deal of data about the vehicle and the soil. Ten different soil parameters have to be specified and are derived with the aid of a development of the Bevameter which is adapted to apply repetitive loading to the soil.

The computer model determines the integrated stresses over the track/soil interface and balances them with the externally applied forces for any given degree of track slip assuming that the track behaves as a flexible elastic belt. Although a later version caters for linked track, it assumes a rigid suspension system of the type used in construction plant.

This method is likely to be useful in vehicle research and development work rather than in commercial and procurement activities, since the programs are difficult to use and very few organisations possess a Bevameter, especially one which will provide repeated loading data. Its particular forte is in predicting mobility in highly deformable terrain such as deep snow.

1B.2.3 HYBRID METHODS

These methods combine theoretical analysis with empirical relationships as appropriate in order to achieve their aim.

1B.2.3.1 NATO Reference Mobility Model (NRMM)

The NRMM is far more than just a soft ground trafficability model. It is designed to simulate the progress of a military vehicle over "real" terrain. The basis of the model is a simulation of a number of samples of actual off-road terrain constructed from detailed surveys. The terrain will typically include several different types of soil. The vehicle is also modelled in some detail and it is 'driven' over the terrain using a suitable route. The average speed of the vehicle to reach a destination from a starting point is taken as a measure of its overall mobility characteristics. This average speed may not necessarily be limited primarily by terramechanic considerations. It is affected by several other factors including power train characteristics, obstacles, driver visibility, vegetation and suspension characteristics.

The model attempts to simulate the types of terrain which might be encountered on-road, on trails and off-road. The off-road terrains include fine-grained soils (clays), coarse grained soils (sands), organic soil (muskeg) and snow. The soil properties vary with the chosen seasonal moisture conditions. For fine-grained soils the terramechanics modelling is based on the MI/VCI approach. For coarse-grained soils a mobility numerics method is adopted, but it uses a different mobility numeric to that commonly employed.

The terramechanics of the problem affects the average speed in two ways. Firstly the model identifies those areas of the terrain which will immobilise the vehicle and chooses a route to avoid them. The poorer the vehicle mobility, the longer the route and the lower will be the average speed. In addition to printing out the average speed it also gives the percentage of terrain which is impassable due to combinations of soil strength and gradient. The latter figures reflect more directly the mobility of the vehicle. The scenario does not include the type of multi-pass situation associated with minefield breaching.

The second effect is the influence of the terrain on the net traction which the vehicle can develop. This will affect the acceleration of the vehicle and, in some circumstances, the maximum possible speed. For fine grained soil, the net traction is calculated from the excess of the vehicle VCI over

the terrain RCI (excess soil strength). For coarse grained soil, equations based on mobility numerics are used. Thus the accuracy of the terramechanics modelling will have a significant effect on the output of the NRMM.

Whilst much of the model is based upon the application of vehicle mechanics theory, it is fair to say that the terramechanics components are largely derived from empirical data.

The NRMM was considerably revised in 1992, the latest version being known as NRMM II. The revisions included some significant changes in the terramechanics modelling. The NRMM II is only available to approved users which include NATO government agencies and defence contractors. It needs trained personnel to operate it who are kept up to date via membership of the NRMM Users Club which meets regularly to share experience and to be advised of developments to the model. In the UK a copy is held and operated by DERA.

1B.4 SUMMARY OF METHODS

Mobility System	Wheels or Tracks	Soil Types	Experimental Validation	Notes
NGP_T	T	-		Over simplistic
MI_T	T	-		Theoretically unsound
MMP_T	T	-	Yes	Basically sound
NGP_W	W	-		Over simplistic and arbitrary
APSG	W	-		Over simplistic and arbitrary
MI_W	W	-		Theoretically unsound
MMP_W	W	-	Some	Indirectly derived
CI_L	W	Clay	Some	Based on MMP
VCI_T	T	Clay	Yes	Sound if measured in field
$VLCI_T$	T	Clay	Yes	Needs further validation
VCI_W	W	Clay	Yes	Sound if measured in field
$VLCI_W$	W	Clay	Yes	Needs further validation
Mobility numerics	W & T	Clay & Sand	Yes	Empirical - plethora of equations
Excess soil strength	W & T	Clay	Yes	Used in NRMM - depends on VCI
Brit Theory	W & T	Clay		Simplistic
Bekker	T	Clay	Some	Complicated - not reliable
Reece	W & T	Clay & Sand	Some	Better than Bekker
Wong	T	Clay & Snow	Some	Complex - potentially good
NRMM	W & T	Clay & Sand	Yes	Uses VCI and mobility numerics

Table 1B1 Mobility Characterisation Systems

1B.5 REFERENCES

1B1 Rowland D "Tracked vehicle ground pressure and its effect on soft ground performance" Proceedings of the 4th ISTVS Conference Stockholm April 1972

1B2 Wong J Y "On the role of MMP as an indicator of cross-country mobility for tracked vehicles" Vol 31 No 3 Journal of Terramechanics 1994

1B3 Littleton I and Hetherington J G "The study of parameters which affect tracked vehicle ground pressure on dry sand" Proc of the 9th International Conference, ISTVS, Barcelona 1987

1B4 Rowland D "Tracked vehicle ground pressure" Report No 72031 MVEE 1972

1B5 Hetherington J G and White J "The measurement of ground pressure under wheeled vehicles" Paper presented at the Wheels and Tracks Symposium RMCS Sept 1988

1B6 Knight S J and Rula A A "Measurement and estimation of the trafficability of fine-grained soils" Proceedings of the International Conference on Soil-Vehicle Systems, Minerva Tecnica, Turin, 1961

1B7 Maclaurin E B "Proposed revisions to MMP based on the results of tractive performance trials with single pneumatic tyres and a modular track system" Report No DERA/LS4/TR970122/1.0 DERA Chertsey 1997

1B8 Bekker M G "Theory of land locomotion" University of Michigan Press 1956

ANNEX 1C DEFINITIONS OF MOBILITY PARAMETERS

1C.1.1 NOMINAL GROUND PRESSURE (Tracked Vehicles)

$$NGP_T = \frac{W}{2bl}$$

Where:
W = gross vehicle weight
b = track width
l = nominal length of track on the ground

1C.1.2 MOBILITY INDEX (Self Propelled Tracked Vehicles)

Note: Imperial units *must* be used in this empirical equation

$$MI_T = \left[\frac{CPF \times WF}{TF \times GF} + WLF - CF\right] EF \times TRF$$

Where :

$$CPF \text{ (Contact Pressure Factor)} = \frac{\text{gross vehicle weight (lbf)}}{\text{area of tracks in contact with the ground (in}^2\text{)}}$$

WF (Weight Factor)
= 1.0 ($W < 50\,000$ lbf)
= 1.2 ($50\,000 \text{ lbf} < W < 69\,999$ lbf)
= 1.4 ($70\,000 \text{ lbf} < W < 99\,999$ lbf)
= 1.8 ($W \geq 100\,000$ lbf)

TF (Track Factor) = 0.01 times track width (in)

GF (Grouser Factor)
= 1.0 (grousers < 1 in high)
= 1.1 (grousers > 1 in high)

$$WLF \text{ (Wheel Load Factor)} = \frac{\text{Gross vehicle weight (lbf)}}{10NA_{shoe}}$$

where N is the number of wheels and A_{shoe} is the area of one track shoe (in^2)

CF (Clearance Factor) = ground clearance (in) / 10

EF (Engine Factor)
= 1.0 (power mass ratio > 10 hp/ton)
= 1.05 (power mass ratio < 10 hp/ton)

TRF (Transmission Factor)
= 1.0 (automatic transmission)
= 1.05 (manual transmission)

1C.1.3 MEAN MAXIMUM PRESSURE (Tracked Vehicles)

$$MMP_T = \frac{1.26W}{2mbe\sqrt{pd}}$$

Where:
- W = gross vehicle weight
- m = number of wheelstations on one track
- b = track width
- p = track pitch
- d = roadwheel diameter
- e = projected area of track plate/ (bp)

1C.2.1 NOMINAL GROUND PRESSURE (Wheeled Vehicles)

$$NGP_W = \frac{W}{2mbR}$$

Where:
- W = gross vehicle weight
- m = number of axles
- b = tyre section width
- R = radius of unloaded tyre

1C.2.2 AVERAGE PRESSURE ON SOFT GROUND (Self Propelled Wheeled (AWD) Vehicles)

$$APSG = \frac{W}{2m \times EAOC}$$

Where $EAOC$ is the effective area of contact defined by

$$EAOC = 2b\sqrt{R^2 - (R' - z)^2}$$

and
- W = gross vehicle weight
- m = number of axles
- b = tyre section width
- R = radius of unloaded tyre
- R' = axle height on hard surface ($= R - \delta$)
- z = sinkage (= 0.075 m)
- δ = tyre static deflection on hard road

Note: In France APSG is known as PMSM (*Pression Moyenne sur Sol Mou*) and EAOC is known as *Pseudo-Aire de Contact.*

1C.2.3 MOBILITY INDEX (Wheeled Vehicles)

Note: Imperial units *must* be used in this empirical equation.

$$MI_W = \left[\frac{CPF \times WF}{TF \times GF} + WLF - CF \right] \times EF \times TRF$$

Where:

CPF (Contact Pressure Factor) $= \dfrac{\text{gross vehicle weight (lbf)}}{bR \times \text{no of tyres}}$

where b = tyre section width (in) and R = tyre radius (in)

WF (Weight Factor)
$= 0.553\,X \quad (X < 2)$
$= 0.033\,X + 1.05 \quad (2 < X < 13.5)$
$= 0.142\,X - 0.42 \quad (13.5 < X < 20)$
$= 0.278\,X - 3.115 \quad (X > 20)$

where X = average axle load = gross vehicle weight (lbf) / (1000 x no of axles)

TF (Tyre Factor) $= \dfrac{10 + \text{tyre section width (in)}}{100}$

GF (Grouser Factor)
= 1.05 (with chains)
= 1.0 (without chains)

WLF (Wheel Load Factor) $= \dfrac{\text{gross vehicle weight (lbf)}}{2000 \times \text{no of axles}}$

CF (Clearance Factor) = ground clearance (in) / 10

EF (Engine Factor)
= 1.0 (power mass ratio > 10 hp/ton)
= 1.05 (power mass ratio < 10 hp/ton)

TRF (Transmission Factor)
= 1.0 (automatic transmission)
= 1.05 (manual transmission)

1C.2.4 MEAN MAXIMUM PRESSURE (Wheeled Vehicles)

Rowland Formula

$$MMP_W = \frac{K \times W}{2mb^{0.85}d^{1.15}\sqrt{\delta / h}}$$

Where:

W = gross vehicle weight
m = number of axles
b = tyre section width
d = tyre unladen carcass diameter (without tread)
δ = tyre static deflection
h = tyre section height (edge of rim to bottom of tread)
K = factor depending on m and proportion of axles driven (see table below)

Number	Proportion of axles driven

of axles	1	2/3	1/2	1/3	1/4
2	3.65		4.4		
3	3.9	4.35		5.25	
4	4.1		4.95		6.05
6	4.6	5.15	5.55	6.2	

Note: a) The inclusion of the number of axles in K is intended to allow for the effect of multiple passes in a rut.

b) If differential locks are fitted the MMP may be considered to improve as follows:

4x2 vehicles	0.98 MMP
4x4 or 6x6 vehicles	0.97 MMP

Maclaurin Formula

$$MMP_W = \frac{1.14 \times W}{2mb^{0.85}d^{1.15}\sqrt{\delta / d}}$$

Where:

W = gross vehicle weight
m = number of axles
b = tyre section width
d = tyre unladen carcass diameter (without tread)
δ = tyre static deflection

1C.3.1 LIMITING CONE INDEX (Tracked Vehicles)

$$CI_{LT} = 0.83 \ MMP_T$$

1C.3.2 VEHICLE CONE INDEX (Tracked Vehicles)

a) **Clay Soils**

$$VCI_T = 7.0 + 0.2MI_T - \frac{39.2}{MI_T + 5.6} \quad (\text{lbf/in}^2) \text{ for one pass}$$

$$VCI_{T50} = 19.27 + 0.43MI_T - \frac{125.79}{MI_T + 7.8} \quad (\text{lbf/in}^2) \text{ for 50 passes}$$

b) **Organic Soils (Muskeg)**

$$VCI_{TMK} = 13.0 + 0.0625\frac{W}{2(b+l)} \quad (\text{lbf/in}^2) \text{ for one pass}$$

Where:

W = vehicle weight (lbf)
b = track width (in)
l = nominal length of track on ground (in)

1C.3.3 VEHICLE LIMITING CONE INDEX (Tracked Vehicles)

$$VLCI_T = \frac{1.63W}{2mbe\sqrt{pd}}$$

1C.4.1 LIMITING CONE INDEX (Wheeled Vehicles)

$$CI_{LW} = 0.83\ MMP_W$$

Where MMP_W is calculated using the Rowland formula

1C.4.2 VEHICLE CONE INDEX (Wheeled Vehicles)

a) **Clay Soils**

For a single pass:

$$VCI_W = 11.48 + 0.2MI_W - \frac{39.2}{MI_W + 3.74} \quad (\text{lbf/in}^2) \quad \text{if } MI_W \leq 115$$

or

$$VCI_W = 4.1MI_W^{0.446} \quad (\text{lbf/in}^2) \quad \text{if } MI_W > 115$$

For 50 passes:

$$VCI_{W50} = 28.23 + 0.43MI_W - \frac{92.67}{MI_W + 3.67} \quad (\text{lbf/in}^2)$$

A correction which allows for variation in tyre inflation pressure for a single pass is as follows:

$$VCI_W = VCI_W\left[\frac{0.15}{\delta / h_0}\right]^{0.25} \quad (\text{lbf/in}^2)$$

where h_o = nominal tyre section height.
δ = tyre static deflection

b) **Organic Soils (Muskeg)**

$$VCI_{WMK} = 13.0 + 0.535\frac{W}{2m(b+d)} \quad \text{for one pass}$$

Where:
W = vehicle weight (lbf)
b = track width (in)
m = number of axles
d = tyre diameter (in)

1C.4.3 VEHICLE LIMITING CONE INDEX (Wheeled Vehicles)

$$VLCI_W = \frac{1.85W}{2mb^{0.8}d^{0.8}\delta^{0.4}}$$

1C.5.1 MOBILITY NUMERICS (Tracked Vehicles)

a) Clay Soils

No mobility numeric was derived for tracks on clay in the original WES study, however Rowland suggested an equivalent numeric based on his MMP as follows:

$$\pi_{ct} = 11.25\left[\frac{0.145\boldsymbol{RCI}}{\boldsymbol{MMP}}\right]^{0.72}$$

where RCI is expressed in units of lbf/in² MMP is in kPa

b) Sand

$$\pi_{st} = \frac{G(bl)^{1.5}}{W}$$

An equation for drawbar pull of tracks on sand at 20% slip due to Turnage is:

$$\frac{D_{20}}{W} = 0.205 + 0.162\log_{10}\pi_{st}$$

where
- G = penetration resistance gradient of the sand
- b = track width
- l = nominal length of track in contact with the ground
- W = gross vehicle weight
- D_{20} = drawbar pull at 20% slip

1C.5.2 MOBILITY NUMERICS (Wheeled Vehicles)

a) Wet clay soils

$$\pi_{cw} = \frac{RCI \times bd\sqrt{\delta / h}}{W}\left[\frac{1}{1 + b/2d}\right]$$

An equation for drawbar pull D at various values of slip due to Harding and Rowland is as follows:

$$\frac{D}{W} = 0.12\pi_{cw}^{0.88}[1 - 0.6(1 - i)^4] - 3(1 + i)(0.01 + \pi_{cw}^{-2.7})$$

where
- RCI = rating cone index of the soil
- b = tyre section width
- d = tyre diameter
- δ = tyre static deflection on hard ground
- h = tyre section height
- W = gross vehicle weight
- D = drawbar pull
- i = longitudinal slip

b) **Sand**

$$\pi_{sw} = \frac{G(bd)^{1.5}}{W_t}\frac{\delta}{h}$$

where:

G = penetration resistance gradient of the sand
b = tyre section width
d = tyre diameter
δ = tyre static deflection on hard ground
h = tyre section height
W_t = vehicle weight per tyre

An equation for drawbar pull derived by WES on sand under field conditions at 20% slip is:

$$\frac{D_{20}}{W} = 0.521 - \frac{12.97}{\pi_{sw} + 19.4}$$

An equation for drawbar pull at various values of slip due to Harding and Rowland is as follows:

$$\frac{D}{W} = 0.36\pi_{sw}^{0.18}[1 - 0.6(1 - i)^4] - 2[1 + k(i - 0.1)](0.01 + \pi_{sw}^{-1.45})$$

where:

D = drawbar pull
W = gross vehicle weight
k = a constant (= 4 for $i > 0.1$, = -2 for $i < 0.1$)

the other notation being identical to that given above.

The following equation for drawbar pull at 15% slip on sand (modified by the inclusion of two minor terms) is used in the NRMM II:

$$\frac{D_{15}}{W} = 0.52 - \frac{396}{\pi_{swn} + 557}$$

where π_{swn} is a pseudo (i.e. dimensional) numeric given by:

$$\pi_{swn} = \frac{CI_{eq}(bd)^{1.5}}{W_t(1 - \delta / h)^3}$$

where

CI_{eq} is related to G by the equation $G = 0.8645\ CI_{eq} / 3$ (lbf/in^3)
b = tyre section width (in)
d = tyre diameter (in)
δ = tyre static deflection on hard ground (in)
h = tyre section height (in)
W_t = vehicle weight per tyre (lbf)

1C.6.1 EXCESS SOIL STRENGTH (Tracked Vehicles)

The following equation is used in NRMM II for fine-grained soils

$$\frac{D}{W} = 0.6512633 - \frac{4.90683}{RCI - VCI + 7.285463} + 0.02224646$$

where:

D = drawbar pull
W = gross vehicle weight
RCI = soil rating cone index ($\mathrm{lbf/in^2}$)
VCI = vehicle cone index ($\mathrm{lbf/in^2}$)

1C.6.2 EXCESS SOIL STRENGTH (Wheeled Vehicles)

The following equation is used in NRMM II for fine-grained soils

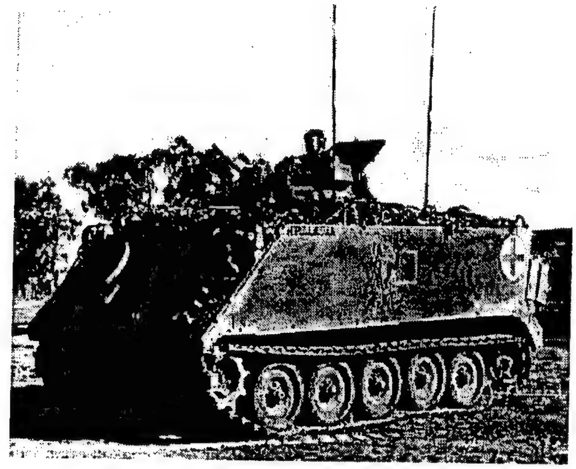
$$\frac{D}{W} = 0.6152356 - \frac{6.183363}{RCI - VCI + 9.258565} + 0.05261765$$

using the same notation as 1C.6.1

ANNEX 1D VEHICLE DATA USED IN TRAFFICABILITY ANALYSIS

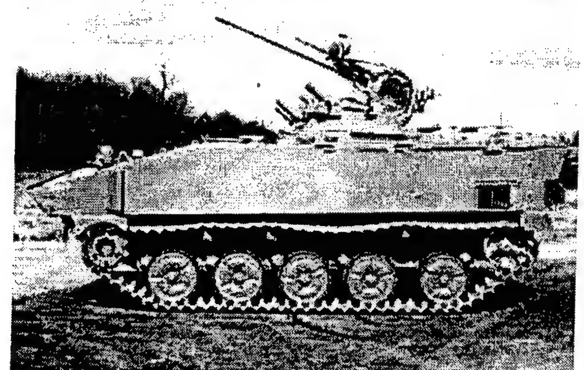
TRACKED AFVs

United Defense LP (USA)
M113-A1 Armoured Personnel Carrier
12.2 US ton (11.07 tonne)
5 wheelstations per side
Torsion bar suspension



Alvis (UK)
Stormer Armoured Personnel Carrier
14.0 US ton (12.7 tonne)
6 wheelstations per side
Torsion bar suspension

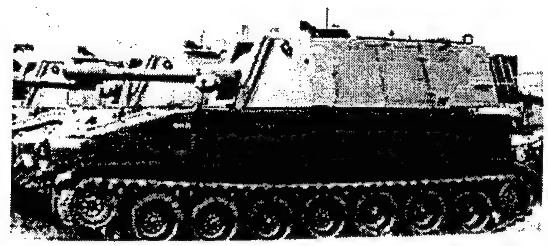
Giat Industries (France)
AMX-10P Infantry Fighting Vehicle
16.0 US ton (14.5 tonne)
5 wheelstations per side
Torsion bar suspension



Steyr-Daimler-Puch (Austria)
SK105-A1 Light Tank
19.5 US ton (17.7 tonne)
5 wheelstations per side
Torsion bar suspension

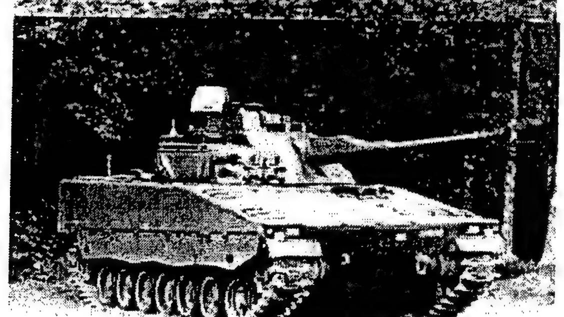
(Russian Federation and Associated States)
BMP-3 Armoured Personnel Carrier
20.6 US ton (18.7 tonne)
6 wheelstations per side
Torsion bar suspension

(USA)
M108 Self-Propelled Howitzer
24.75 US tonne (22.45 tonne)
7 wheelstations per side
Torsion bar suspension



Cadillac Gage (USA)
Stingray II Light Tank
24.9 US ton (22.6 tonne)
6 wheelstations per side
Torsion bar suspension

Bofors/Hagglunds Vehicle (Sweden)
CV9040 Infantry Fighting Vehicle
25.1 US ton (22.8 tonne)
7 wheelstations per side
Torsion bar suspension

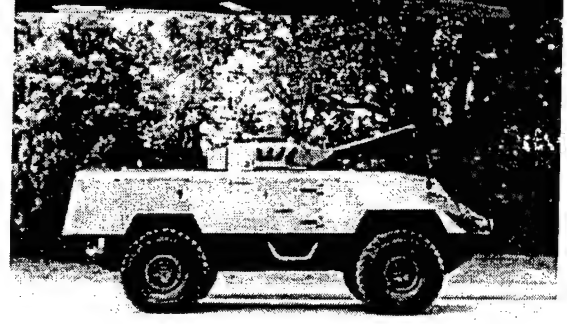


WHEELED AFVS

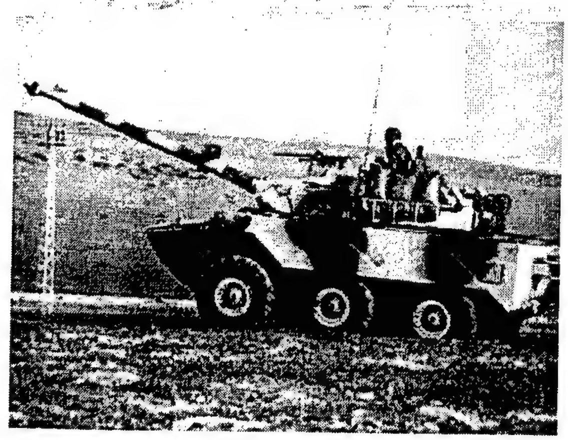
Steyr-Daimler-Puch (Austria)
Pandur Armoured Personnel Carrier
14.88 US ton (13.5 tonne)
6x6 with 12.5R20 tyres and CTIS
Hybrid suspension linkage with coil springs (front)
Torsion bar suspension (rear)

(Russian Federation and Associated States)
BTR-80 Armoured Personnel Carrier
15.0 US ton (13.6 tonne)
8x8 with 13.00-18 tyres and CTIS
Transverse link suspension with torsion bars

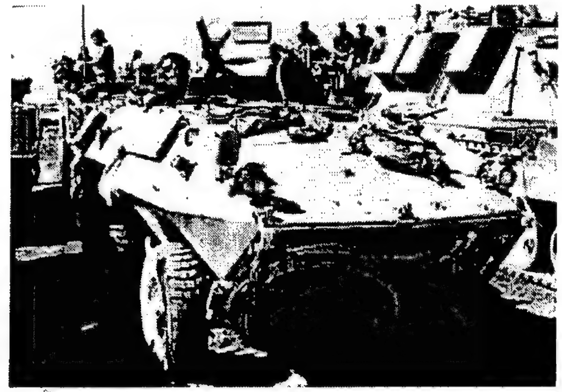
Greys Defence Systems (UK)
Panther Multi-Role Combat Vehicle
15.4 US ton (14 tonne)
4x4 with 16.00R20 tyres and CTIS
Double wishbone suspension with coil springs



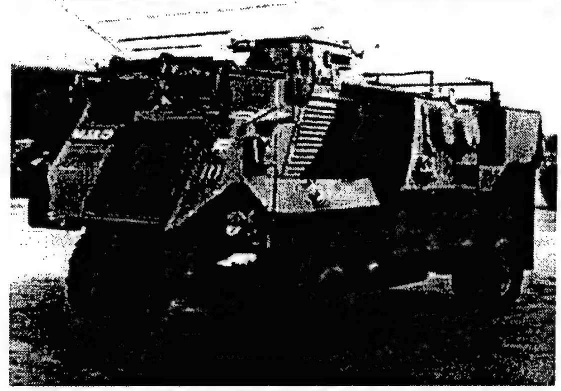
Giat Industries (France)
AMX-10RC Reconnaissance Vehicle
17.5 US ton (15.88 tonne)
6x6 with 14.00R20 tyres and CTIS
Trailing link hydrogas suspension, skid steer



General Motors Canada (Canada)
Grizzly Armoured Personnel Carrier
11.6 US ton (10.5 tonne)
6x6 with 11.00-16 tyres
Strut suspension with coil springs (front)
Torsion bar suspension (rear)



GKN (UK)
Saxon Armoured Personnel Carrier
12.9 US ton (11.66 tonne)
4x4 with 14.00x20 tyres
Beam axle and leaf spring suspension



General Motors Canada (Canada)
LAV-25 Armoured Personnel Carrier
14.1 US ton (12.8 tonne)
8x8 with 11.00-16 tyres
Strut suspension with coil springs (front)
Torsion bar suspension (rear)

Henschel Wehrtechnik (Germany)
Fuchs Armoured Personnel Carrier
20.9 US ton (19 tonne)
6x6 with 14.00R20 tyres
Beam axle and coil spring suspension

Tracked AFV Data for Trafficability Analysis

		M113A1	Stormer	AMX-10P	SK105-A1	BMP-3	M108	Stingray II	CV9040
Combat mass	tonne	11.07	12.7	14.5	17.7	18.7	22.45	22.6	22.8
No of wheelstations		10	12	10	10	12	14	12	14
Wheel diameter	m	0.56	0.584	0.597	0.55	0.55	0.6	0.6	0.6
Track width	m	0.381	0.41	0.425	0.38	0.38	0.381	0.381	0.533
Track pitch	m	0.153	0.116	0.135	0.145	0.15	0.152	0.153	0.152
Track area ratio		0.97	0.87	0.9	0.95	0.95	0.95	0.95	0.93
Track on ground	m	2.667	3.12	2.93	3.037	4.06	3.962	3.632	3.98
Ground clearance	m	0.41	0.425	0.45	0.4	0.4	0.451	0.46	0.45

Note: Values of a few of the above parameters have been scaled from drawings

Wheeled AFV Data for Trafficability Analysis

		Pandur 6x6	BTR-80 8x8	Panther 4x4	AMX-10RC 6x6	Grizzly 6x6	Saxon 4x4	LAV-25 8x8	Fuchs 6x6
Combat mass	tonne	13.5	13.6	14.0	15.88	10.5	11.66	12.79	19.0
No of wheelstations		6	8	4	6	6	4	8	6
Tyre diameter	m	1.033	1.117	1.343	1.254	0.984	1.254	0.984	1.254
Tyre width	m	0.338	0.330	0.438	0.366	0.287	0.366	0.287	0.366
Tyre deflection	m	0.084	0.105	0.133	0.119	0.037	0.062	0.037	0.062
Nominal section height	m	0.263	0.330	0.418	0.373	0.289	0.373	0.289	0.373
Ground clearance	m	0.43	0.475	0.55	0.35	0.5	0.29	0.5	0.406
CTIS		Yes	Yes	Yes	Yes	No	No	No	No

Tyre dimensions taken from Maclaurin E B "Proposed revisions to MMP based on the results of tractive performance trials with single pneumatic tyres and a modular track system" Report No DERA/LS4/TR970122/1.0 DERA Chertsey 1997, from Michelin "Technical data (truck tyres)" Edition No 20 May 1999 and estimated where data not available.

In calculating MMP for vehicles with CTIS, tyre deflection has been taken as 40% of section height assuming "emergency" inflation pressure.

ANNEX 1E GRAPHS OF TRAFFICABILITY PREDICTIONS

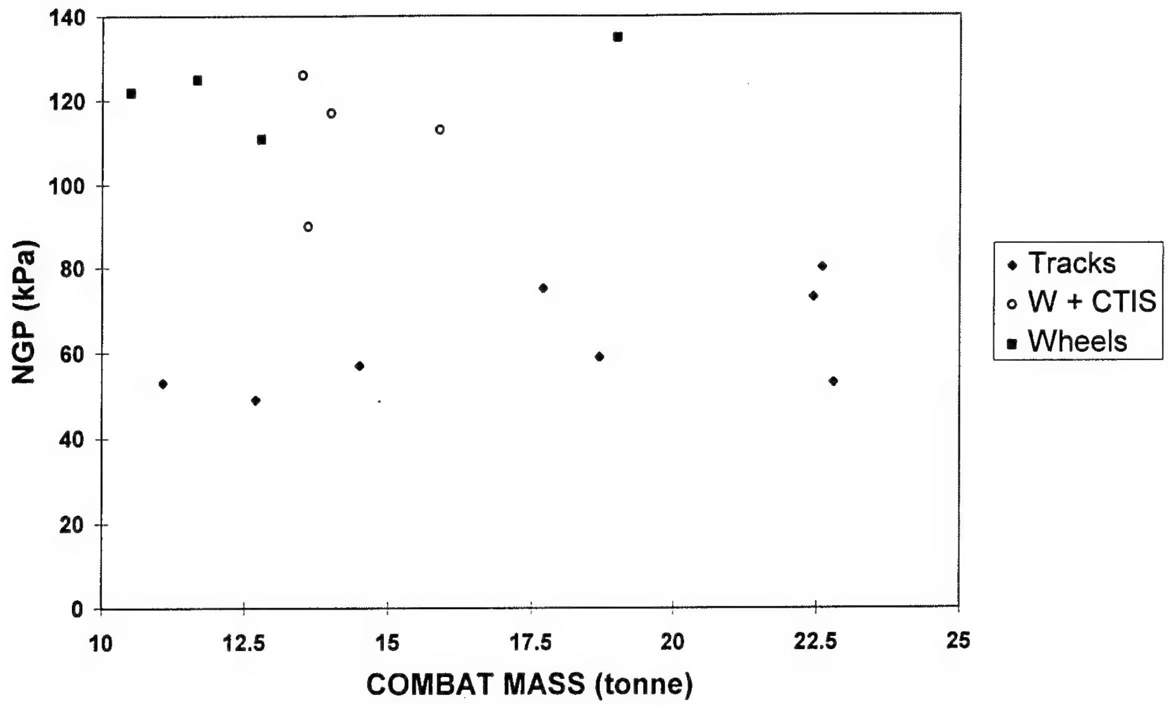


Figure 1E-1 Nominal Ground Pressure

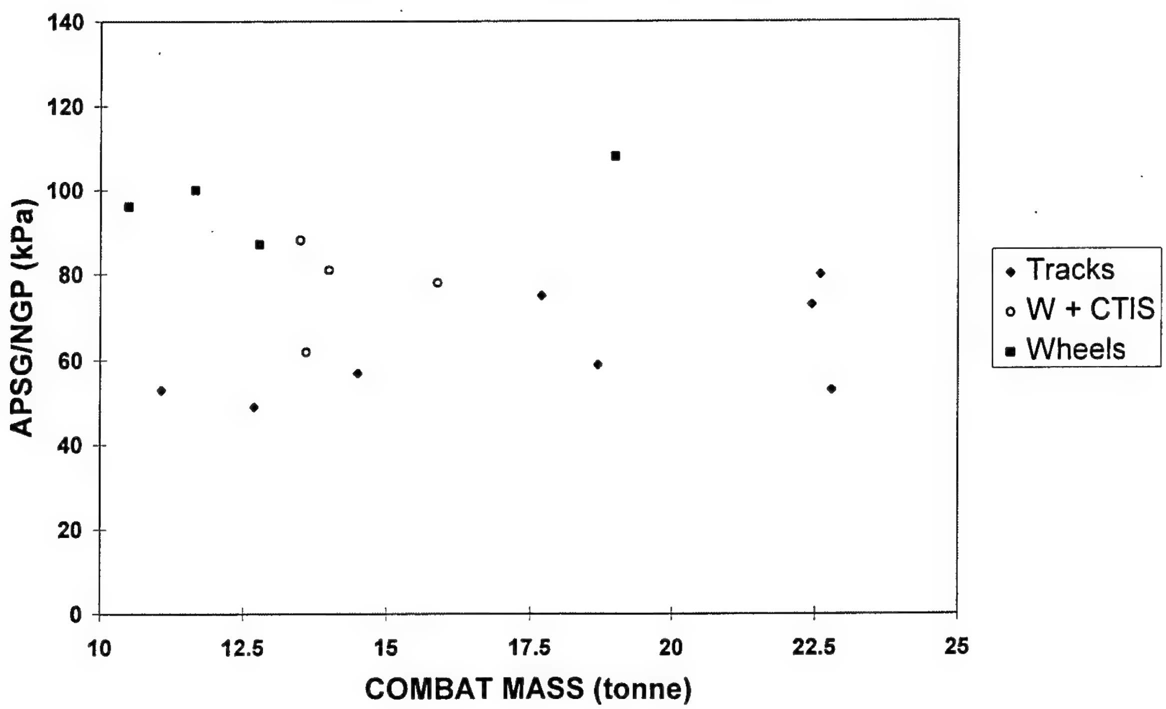


Figure 1E-2 APSG (wheels) and NGP (tracks)

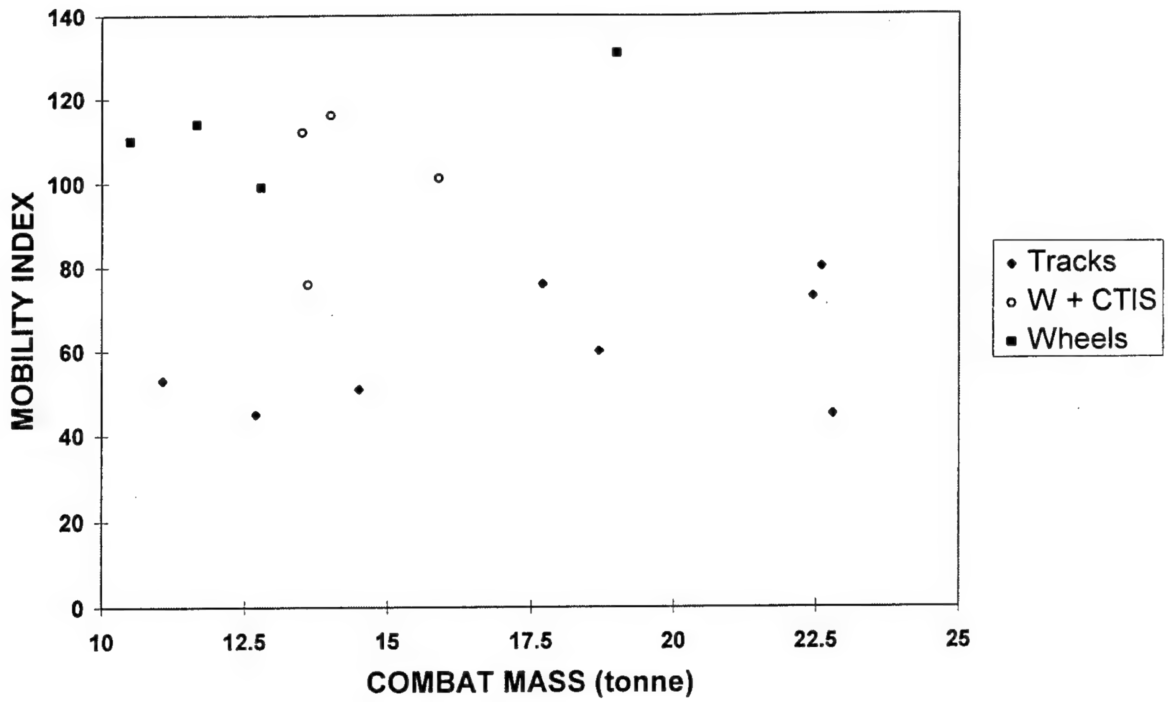


Figure 1E-3 Mobility Index

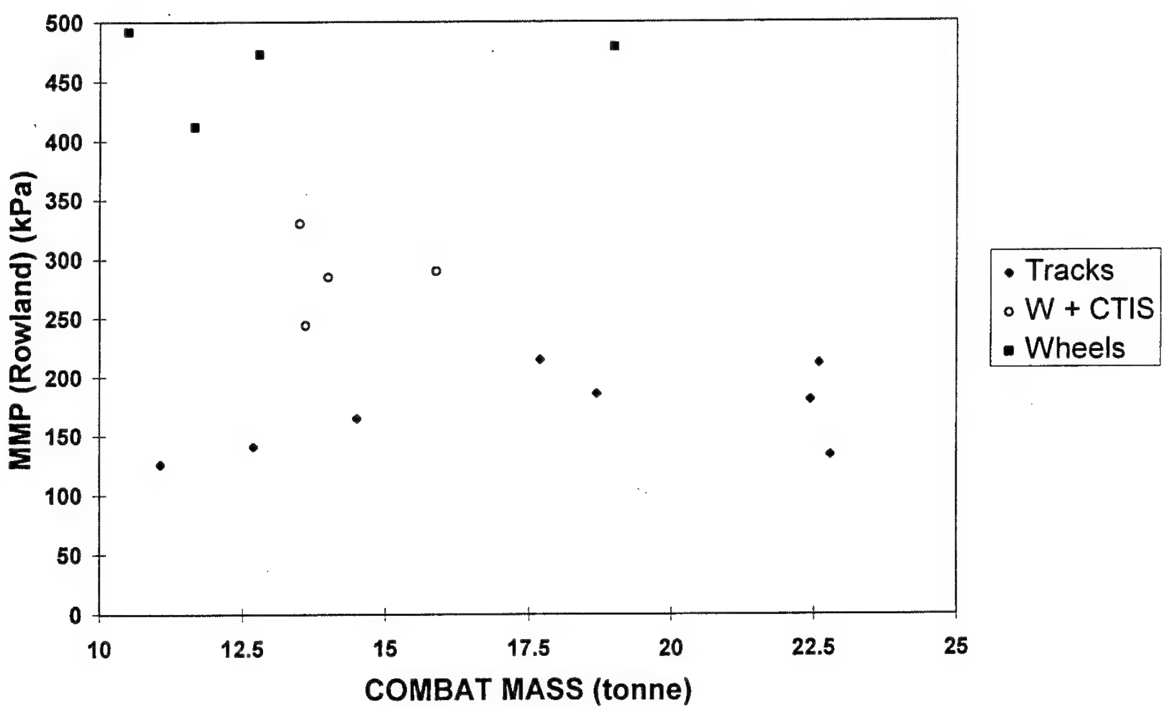


Figure 1E-4 Mean Maximum Pressure (Rowland)

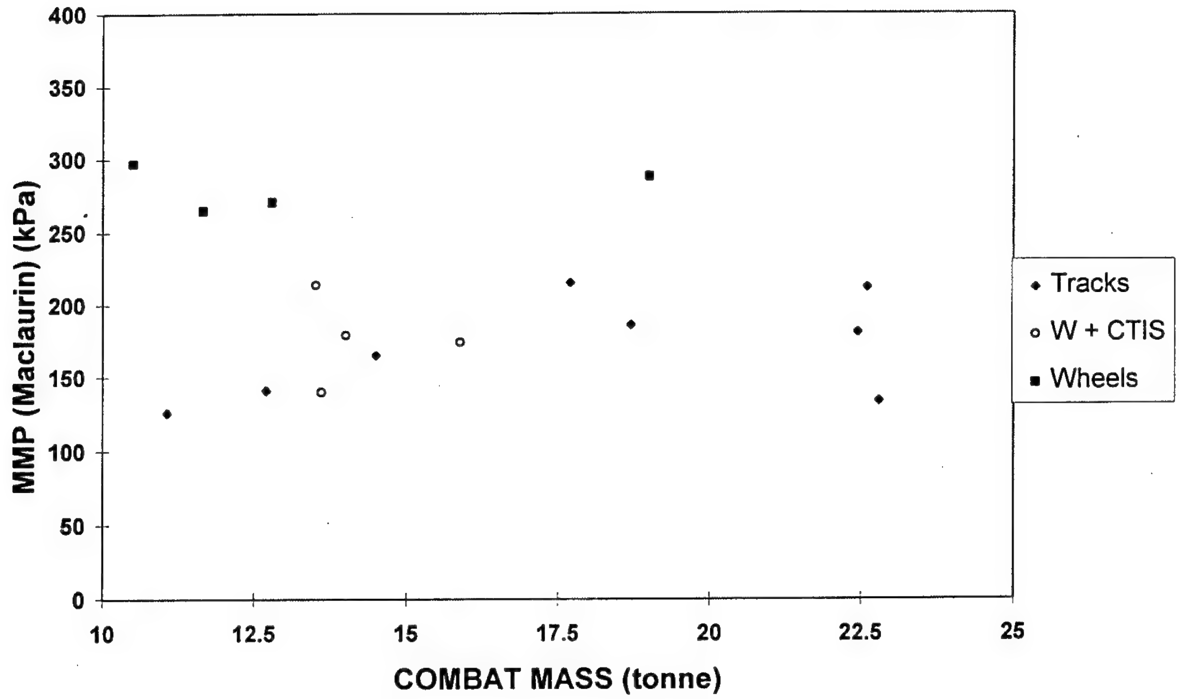


Figure 1E-5 Mean Maximum Pressure (Maclaurin)

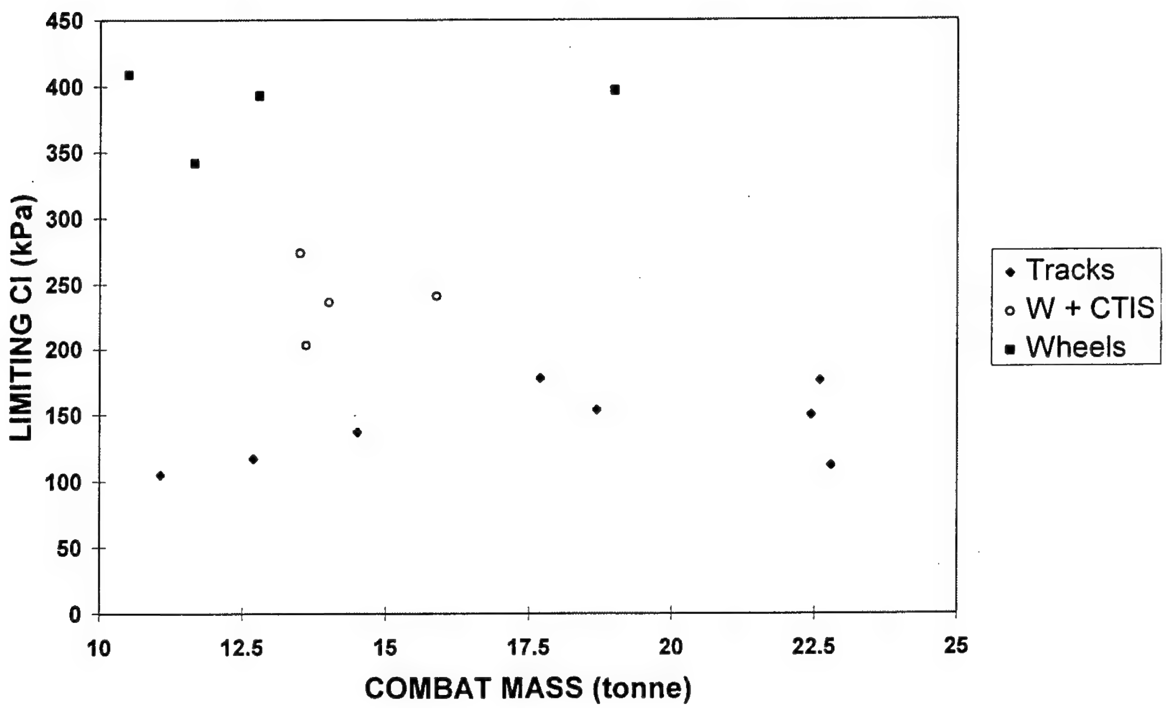


Figure 1E-6 Limiting Cone Index (clay)

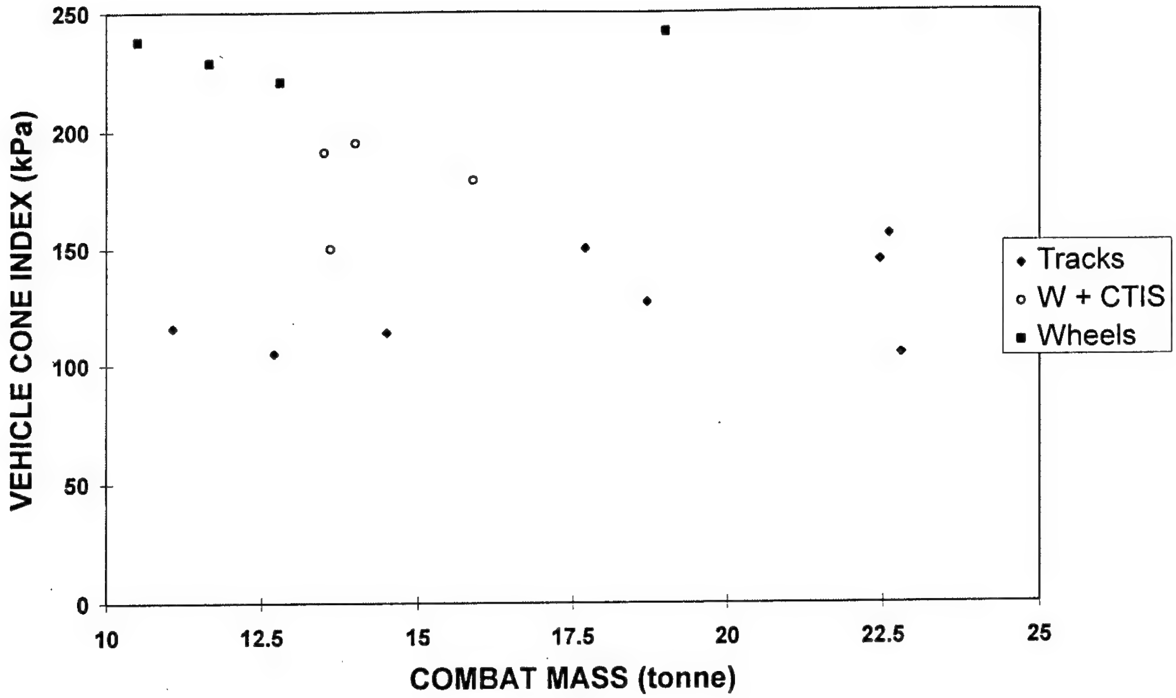


Figure 1E-7 Vehicle Cone Index

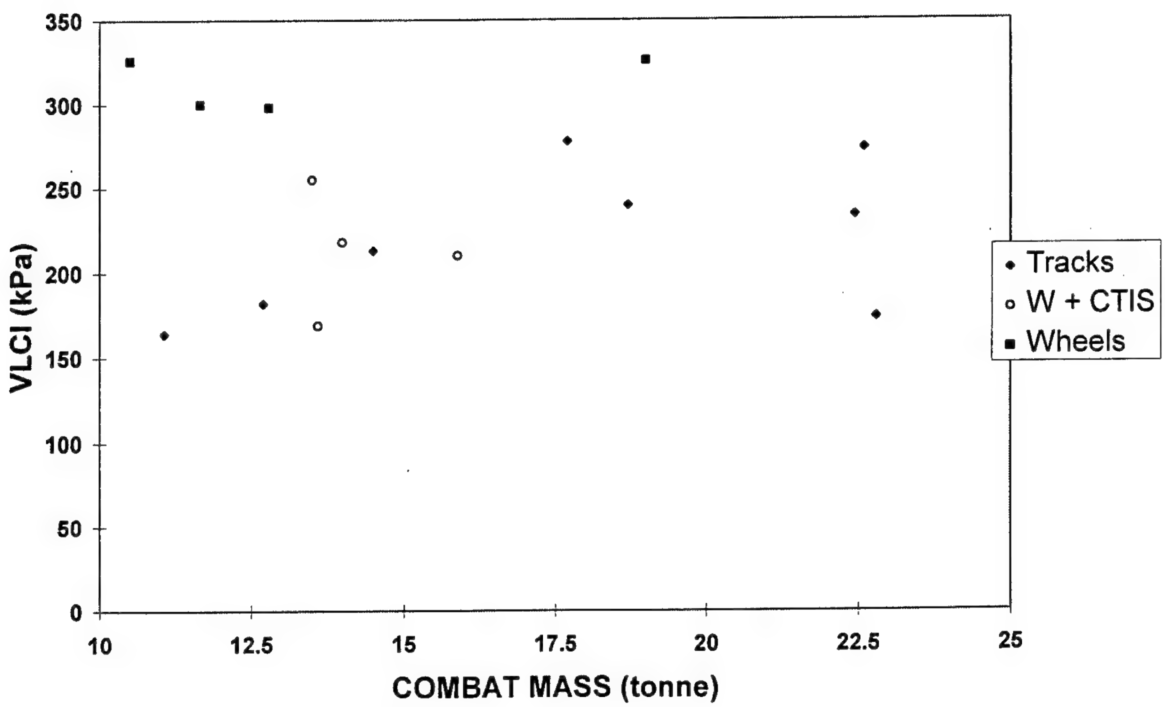


Figure 1E-8 Vehicle Limiting Cone Index (clay)

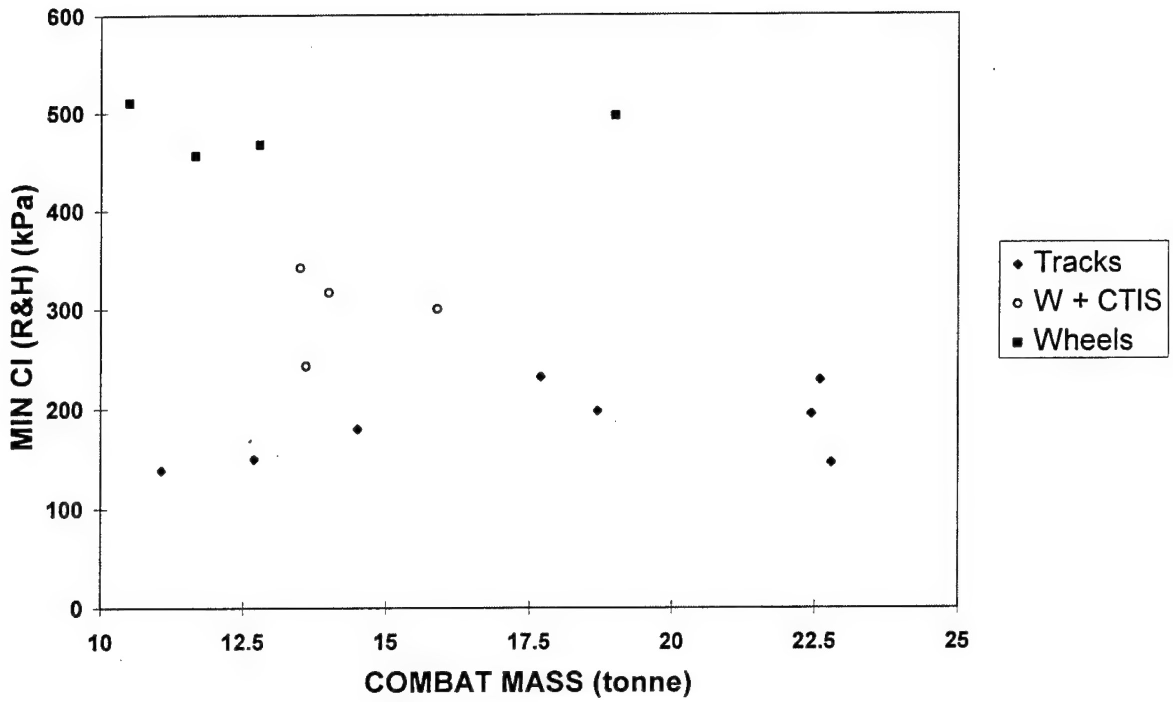


Figure 1E-9 Minimum Cone Index on Clay (Rowland & Harding)

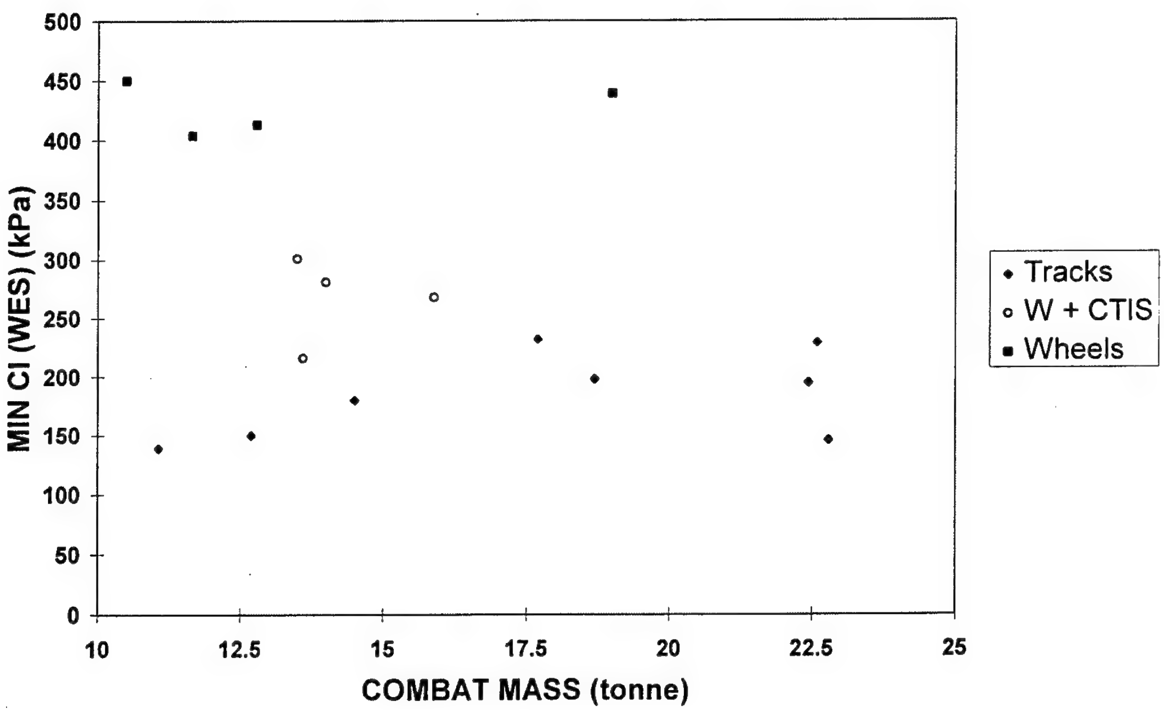


Figure 1E-10 Minimum Cone Index on Clay (WES)

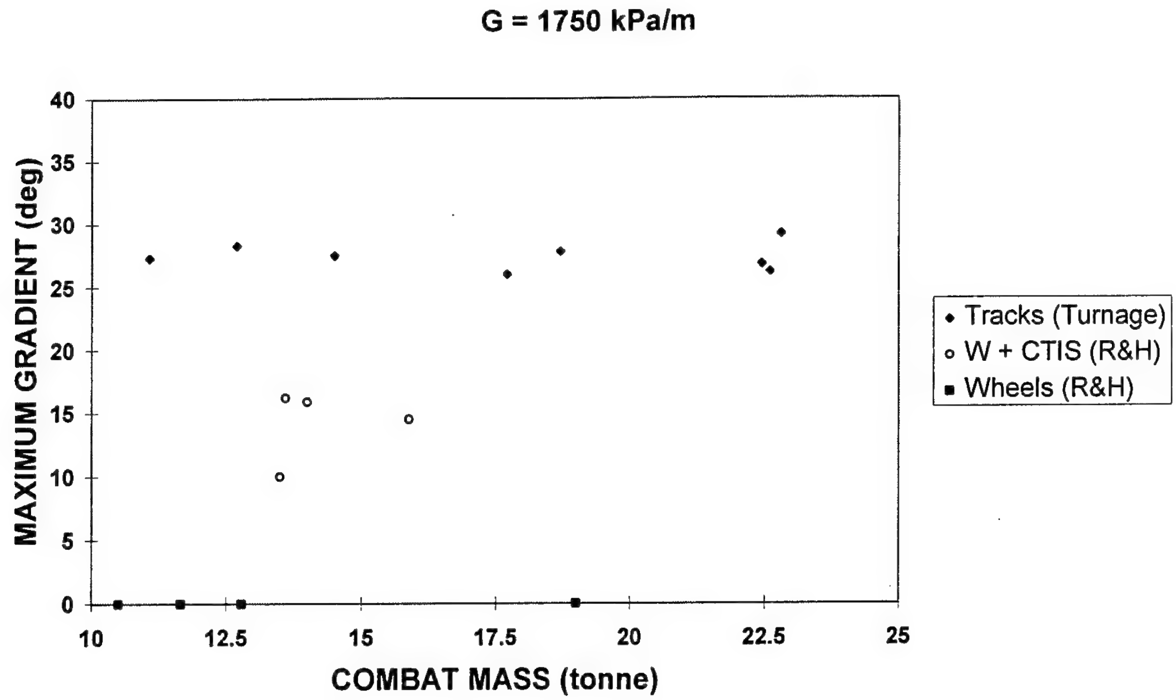


Figure 1E-11 Max Gradient on Soft Sand - Tracks (Turnage) - Wheels (R&H)

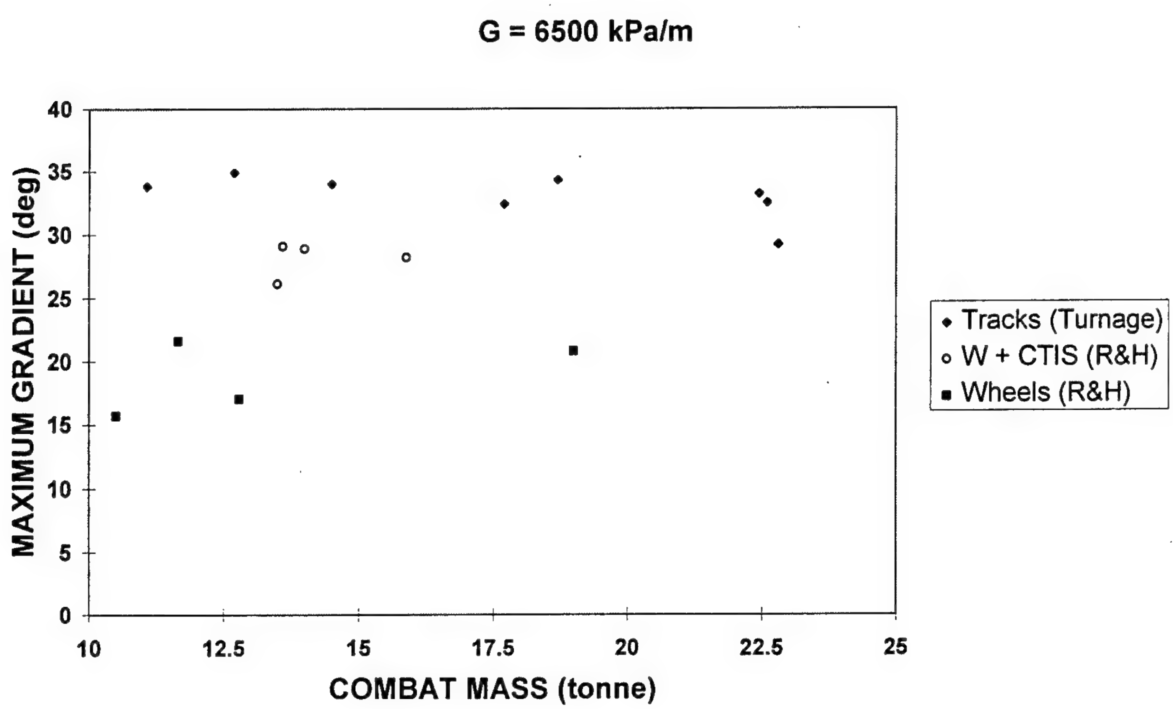


Figure 1E12 Max Gradient on Firm Sand - Tracks (Turnage) - Wheels (R&H)

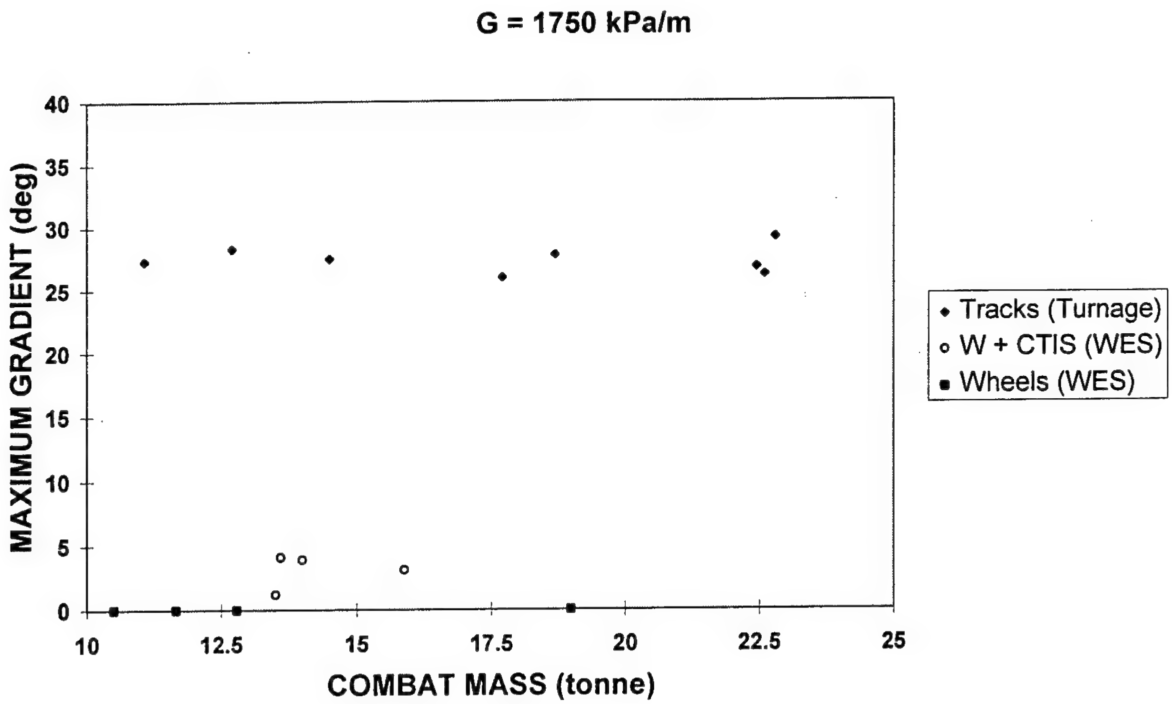


Figure 1E-13 Max Gradient on Soft Sand - Tracks (Turnage) - Wheels (WES)

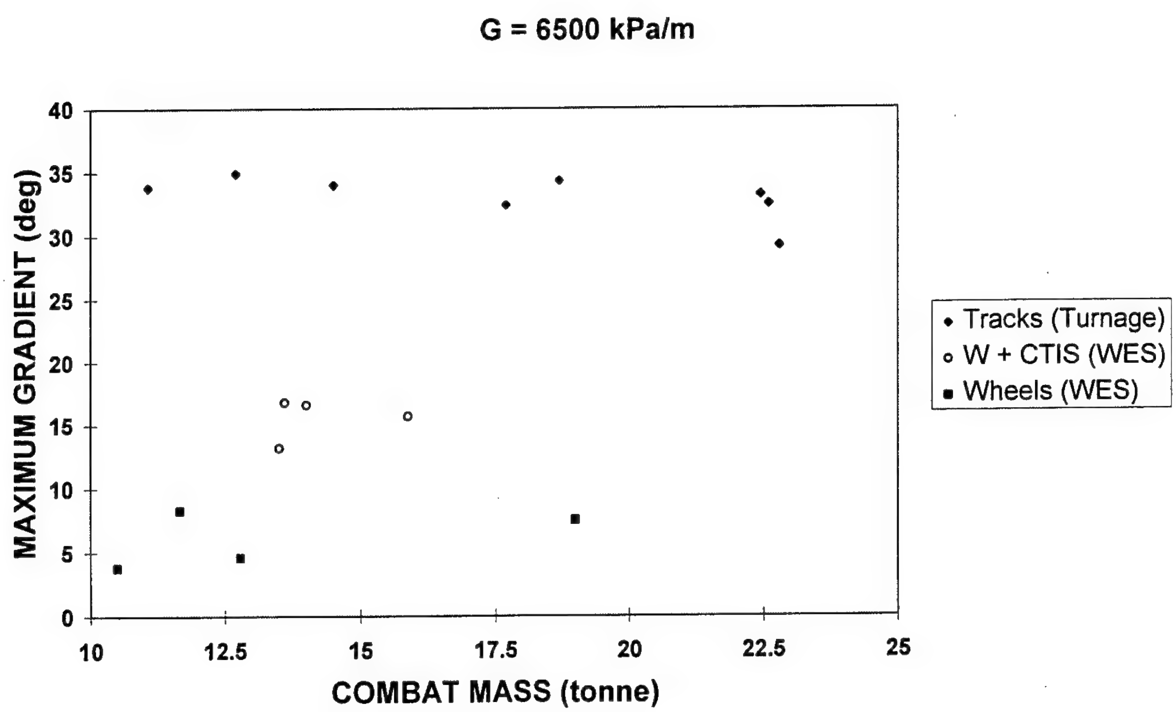


Figure 1E-14 Max Gradient on Firm Sand - Tracks (Turnage) - Wheels (WES)

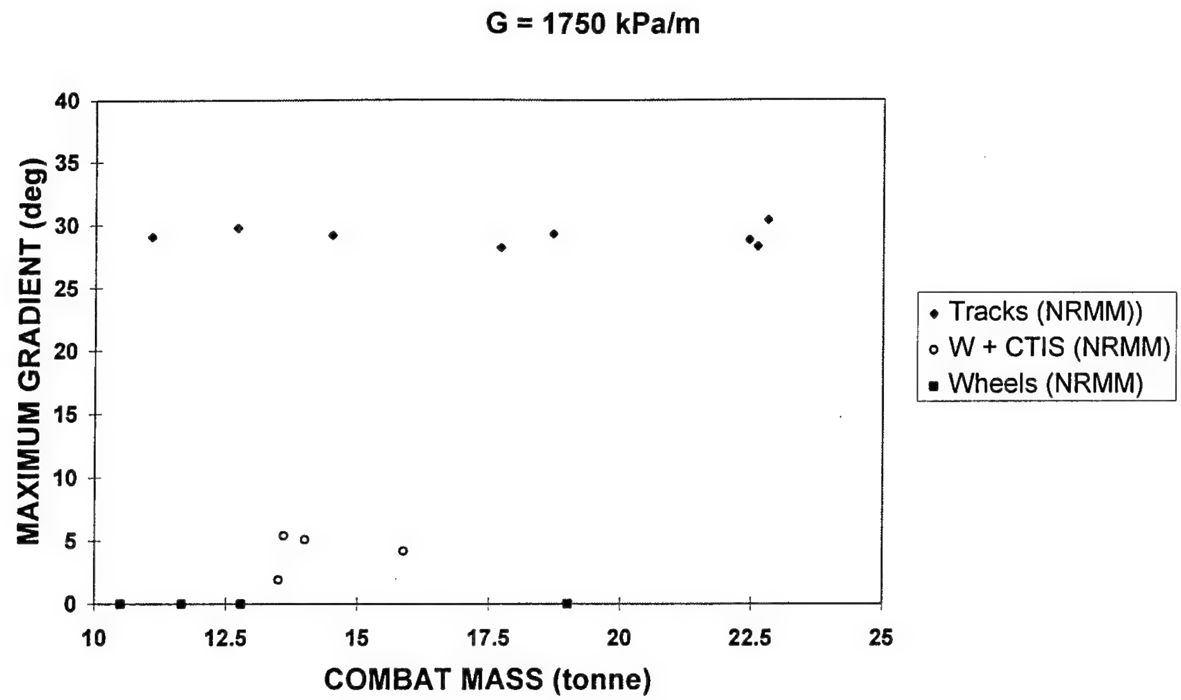


Figure 1E-15 Max Gradient on Soft Sand - NRMM

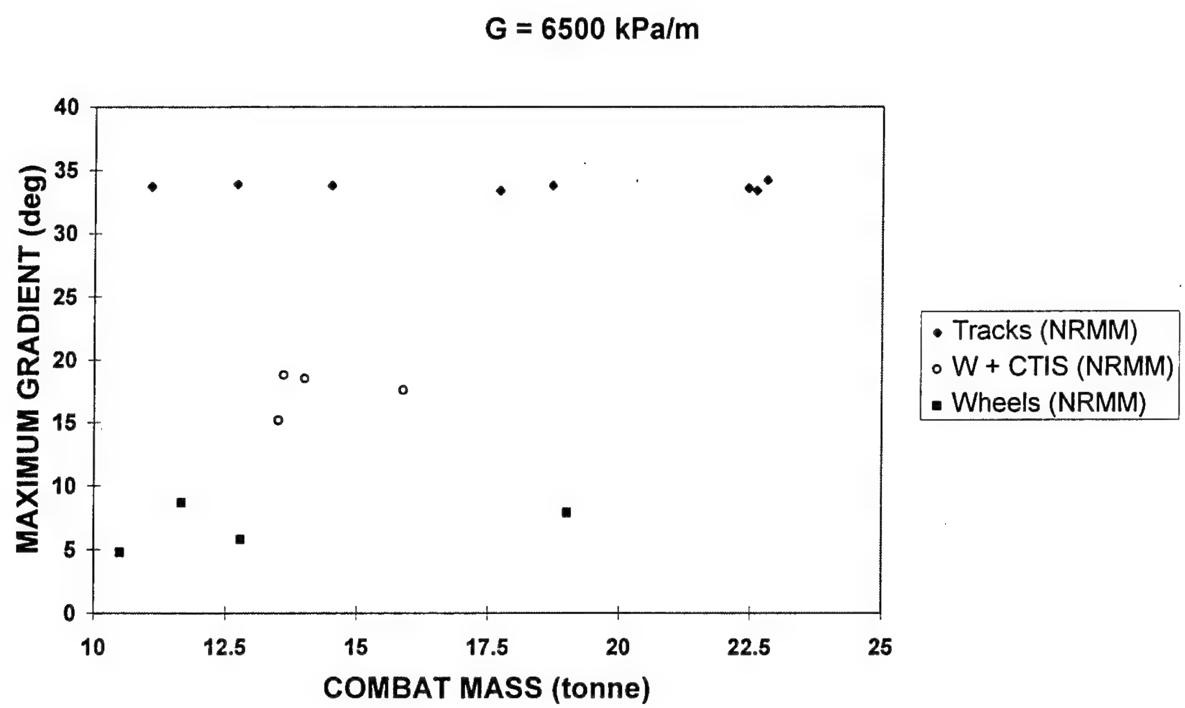


Figure 1E-16 Max Gradient on Firm Sand - NRMM

2 SUSPENSION AND AUTOMOTIVE PERFORMANCE

This Section deals with the effects of the suspension and transmission on vehicle acceleration, sustained velocity and fuel consumption, under various operating conditions.

Two basic vehicles have been considered, one tracked and one wheeled, each having a combat mass of approximately 20 US tons.

Section 2.1 discusses qualitatively the effect of suspension type. Sections 2.2 and 2.3 describe briefly two mathematical models, one each for the suspension and the power train, for the prediction of automotive performance. The results of computer simulations using these models are presented for a range of vehicle and terrain data.

2.1 EFFECT OF SUSPENSION TYPE ON AUTOMOTIVE PERFORMANCE

The design of the suspension system of an AFV has a significant influence on its automotive performance. A discussion of suspension properties and their performance implications is given below for AFVs in the weight range 10 to 25 US tons. Since such vehicles will be expected to offer a good off-road capability it is assumed, in the case of wheeled AFVs, that an all-wheel drive transmission system is employed.

2.1.1 Suspension Properties which Affect Performance

Suspension Travel

If the suspension hits the bump stops on an AFV moving at speed across country, the hull of the vehicle may experience high impact accelerations to the detriment of the structure, the payload and the crew. On a given terrain at a given speed the probability and severity of bump stop impacts are reduced where the bump travel is large. Alternatively, higher speeds become practicable over given terrain for a given level of discomfort. High levels of bump travel adversely affect the packaging of the vehicle, and the bump travel must be appreciably less than the ground clearance under the hull to inhibit impact with the ground.

High levels of rebound travel are advantageous in maintaining ground contact and hence control of the vehicle over rough terrain. Many military vehicles do not fit rebound stops. However, bump and rebound travel may have to be limited on wheeled vehicles to protect universal joints in the driveline from excessive articulation. Where the suspension employs coil springs, rebound stops may be necessary to maintain spring location on full rebound. For tracked vehicles the tracks will ultimately limit full rebound, and the sponsons may be used as the bump stops.

Unsprung Mass

Suspension systems with a low unsprung : sprung mass ratio offer better ride characteristics and maintenance of ground contact at high speed over rough terrain. The latter is not so important for tracked vehicles where the roadwheels are not called upon to transmit traction and braking forces, and which do not rely on friction between the wheels and the tracks to generate cornering forces. Paradoxically, the unsprung mass of tracked AFVs is inherently lower than that of wheeled AFVs, which normally includes brakes, hub reduction gearboxes and large wheels and tyres, usually with run-flat inserts.

It should be noted that in tracked vehicles with conventional tensioned track architecture, the track is not part of the unsprung mass. That length of the track on the ground can be considered as part of the terrain whilst the remainder is supported by the hull via the sprocket, idler and return rollers.

Suspension Load-Deflection Characteristic

It is desirable, in vehicles capable of high off-road speed, that the suspension system offers a rising rate characteristic, i.e. the wheel rate (the gradient of the wheel load-deflection characteristic) rises with suspension deflection. Such a characteristic inhibits violent contact with the bump stop and reduces the resultant impact accelerations experienced by the hull. Some springs are inherently linear, and a rising rate can only be provided by employing non-linear linkage kinematics, fitting progressive bump stops, supplementary springs or other devices.

Effective Wheel Rate

The kinematics of suspension system linkages can influence the effective wheel rate of a suspension when it encounters undulations in the terrain. Typically, when a wheel encounters a bump, for example a small boulder, the resultant force acting on the wheel is at an angle to the vertical. The stiffness of the suspension in this direction may be higher or lower than that in response to a vertical force. Linkages which offer an effective wheel rate which is higher than the vertical wheel rate can result in the generation of high fore and aft accelerations of the hull, which degrade the ride and can result in high stresses on suspension components.

Coulomb Friction

Some suspension components introduce significant levels of Coulomb or sliding friction. This introduces a frictional *dead zone* into the action of the system, in which the suspension is effectively locked solid. The ride quality in this zone is dependent on the tyres and any other resilient elements in the system, and the greater the proportion of time the suspension is locked up, the worse the ride is likely to be. A system with high levels of Coulomb friction is likely to be locked up most of the time on paved road surfaces. Modern AFV suspension systems usually have minimal Coulomb friction.

2.1.2 Performance Characteristics of Suspension Linkages

As explained in Section 1.3.2 there are two basic categories of AFV suspension system, those employing live axles and those using independently sprung wheelstations.

Axles

AFVs employing live axles have a high unsprung : sprung mass ratio. Not only does the live axle comprise the wheels, tyres, brakes and hub reduction gearboxes but, in addition, it includes the axle casing, half shafts, final drive and differential gears, together with any traction control devices such as differential locks. This results in a high unsprung mass to the detriment of ride and roadholding.

To ensure an acceptable ride this bulky axle assembly has to move through an adequate suspension travel relative to the hull, which requires space under the vehicle, and has an adverse effect on mass centre height and silhouette. As a result, frontal area will be increased reducing performance in high speed vehicles. The high mass centre is detrimental to stability and handling and incurs large weight transfer under braking and cornering.

It is normal to use trailing links to provide longitudinal location of axles. In low performance AFVs these may take the form of leaf springs pivoted at their front and shackled at their rear. This form of location reduces the effective wheel rate of the suspension which, in turn, improves the ride on rough terrain.

Independent Suspension

The vast majority of AFVs employ independent suspension systems, since they offer much better packaging, and lower unsprung mass, than axles. There are two basic categories of linkage in use, those relying on longitudinal links, and those based on transverse links, as described in Section 1.3.2. Occasionally, hybrid linkages, which have features of both types, are to be found in this type of vehicle.

Longitudinal link independent suspensions are widely used in AFVs. The single trailing link design is particularly simple and used almost universally on tracked AFVs. It is also found on some wheeled AFVs, particularly on the unsteered axles. This type of suspension offers a low effective wheel rate over rough terrain which is beneficial for ride and suspension reliability. However, trailing link suspensions also introduce relatively large wheel camber changes on corners which affect the handling of wheeled vehicles.

Transverse link independent suspensions are normally used on steered axles. In AFVs they are usually of the classic double wishbone design, but strut based systems are becoming more popular. A transverse link system is more complicated than a single trailing link but allows the designer to tune the suspension kinematics to improve the dynamic behaviour of the vehicle.

In both types of suspension non-linearity can be introduced into the wheel load-deflection characteristic by suitable design of the geometry.

2.1.3 Dynamic Elements

Springs

AFV springs are usually based on either steel or high pressure hydrogas systems.

Steel springs may be in the form of leaf springs, torsion bars or coil springs. Leaf springs offer a basically constant stiffness but may be made into dual-stiffness springs with the aid of helper leaves. Suspension travel is usually limited by spring stress. For large travel, the springs need to be long, in which case they do not give adequate location for the axle. The problems associated with the high Coulomb friction of multi-leaf springs can be overcome by using a single leaf design, but this limits suspension travel.

Torsion bars are widely used in tracked AFVs. They give a constant rate which imposes compromise between soft springing and bottoming of the suspension on rough terrain. The suspension travel is limited by the length of the torsion bar which, in turn, is limited by hull width if mounted transversely. More complex *hair-pin* torsion bars, or *tube-over-bar* layouts, can be employed to increase suspension travel. The main attraction of the single torsion bar is its simplicity.

Coil springs are widely used in wheeled AFVs. They usually have a constant rate, but can be given a rising rate by variation of coil spacing, use of taper wire, or varying coil diameter. They impose no inherent limit on bump travel, and are cheap and readily available.

High pressure hydrogas suspension units have an inherently rising rate which is ideal for high speed operation on rough terrain. They have no inherent bump travel limitations but are relatively sophisticated and expensive. With added control technology, and cost, they can provide variable ride height, attitude control and semi-active behaviour.

Dampers

Damping in AFV suspension systems is essential to ensure good ride and roadholding.

There are very few AFVs with Coulomb damping. In its basic form it leads to a dead zone in the suspension characteristic, and hence poor ride. Some vehicles use a more sophisticated design in which the damper frictional preload is varied , usually in proportion to suspension deflection. This type of damper can give very good results at high cross-country speeds.

Most AFVs use viscous dampers, fitted with some form of pressure relief valve to prevent damage at high damper velocity. One of the keys to success in off-road vehicles is to provide good cooling for the dampers. The widely used telescopic damper is difficult to cool and often becomes unreliable as a consequence, leading to serious reductions in ride quality. Lever-arm and rotary dampers, which are bolted directly on to the hull, give much better results, particularly where the hull is fabricated from aluminium alloy.

There is serious interest in the possibility of introducing variable damping technology into AFVs, either adaptively to optimise the rate for a particular terrain, or semi-actively to give a continuously variable rate using a high bandwidth control system.

2.2 SUSPENSION PERFORMANCE

As part of this study, the effect of the suspension parameters on the vehicle performance has been investigated using a computer simulation to predict the suspension loads, and hence vehicle movement, as the vehicle traverses a series of terrain profiles at a number of nominally constant speeds. In all cases, it is assumed that the vehicle has adequate tractive effort.

2.2.1 Vehicle Models

Both the tracked and the wheel vehicles are modelled in side elevation, as shown in Figure 2.1.

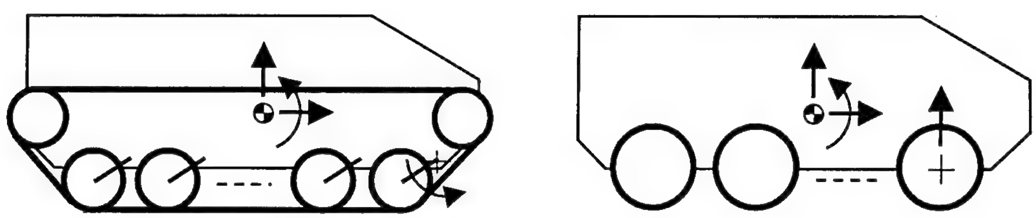


Figure 2.1 Tracked and Wheeled Vehicle Suspension Models

The tracked vehicle model has a rigid hull and a number of wheel stations, each comprising a road wheel and trailing arm, giving $3 + n$ degrees of freedom (3 for the hull and one for each of the n wheel stations) with positive senses as shown. The suspension characteristic is defined by wheel arm torque as a function of wheel arm angular displacement, as if the springing is provided by a torsion bar. However, this characteristic need not be linear, and hence may include bump and rebound stop characteristics, and the effects of any geometry and non-linear elements such as hydrogas systems. The damper, which may also be non-linear, is defined by wheel arm torque as a function of both wheel arm angular displacement and velocity. Both the stiffness and damping characteristics may be defined differently for each wheel station. Hull and running gear geometry, masses and moments of inertia, and track properties are also defined in the model.

The wheeled vehicle model is defined in a similar manner, except that the wheel degree of freedom is assumed to be vertical, hence stiffness and damping characteristics are represented by vertical wheel rates. The effects of any suspension linkage must be incorporated into the wheel rate characteristics by prior calculation. Tyre stiffness and damping properties are also included.

For both models, account is taken of loss of ground contact by any wheel.

2.2.2 Terrain Model

The terrain is assumed to be rigid and its profile is represented by a series of ordinates at equal horizontal spacing. The geometric interaction between the finite wheel diameter and the terrain profile is included, with linear interpolation as necessary. Experience has shown that little is gained by using data more closely spaced that about one fifth of the wheel diameter, and a coarser mesh is frequently adequate.

2.2.3 Vehicle Data

Three tracked vehicles have been modelled for this study, each having five equally spaced wheel stations. The suspension geometry is the same for all vehicles. Two of the vehicles, designated TR-1 and TR-2, have the same linear spring characteristic such as might be obtained from the use of a torsion bar, arranged to give a bounce natural frequency of about 1.5 Hz, but with a low and medium bump travel (200 mm for TR-1 and 250 mm for TR-2). The third vehicle, designated TR-3, has a hardening spring characteristic, such as might be given by a hydrogas unit. This characteristic is arranged to give the same bounce natural frequency (1.5 Hz) at the equilibrium position, but has a higher (300 mm) bump travel. For all three tracked vehicles the same damping characteristic is applied to the first, second and fifth wheel stations only. This characteristic is based on that of a typical AFV damper, scaled to suit the vehicle weight. Details of the tracked vehicle data are given in Annex 2A.

Three wheeled vehicles have also been modelled. The first vehicle, designated WH-1, has four equally spaced axles with identical suspension characteristics. The second vehicle, designated WH-2, is similar but has three axles. The third vehicle, designated WH-3, also has three axles, but close coupled at the rear. The bump travel has been limited to 200 mm in all cases The spring and damping rates have been chosen to give similar hull natural frequencies and damping ratios as the tracked vehicles However, for WH-3 the spring preloads were adjusted to give a horizontal hull static attitude. Details of the wheeled vehicle data are given in Annex 2B.

2.2.4 Terrain Data

Three terrain profiles have been used:

a. Ramp up followed by ramp down, 1.5 m overall length, 200 mm high.

b. Eight cycles of sine wave, 7 metre wavelength, 100 mm peak-to-peak.

c. A section of random terrain, 204 m long, mean and rms heights of 0.428 and 0.137 m respectively, -6dB per octave spatial power spectral density.

Details of these profiles are given in Annex 2C.

2.2.5 Tracked Vehicle Suspension Performance Results

The model generates a significant range of data. A plot of a typical selection appropriate to this study is shown in Figure 2-2.

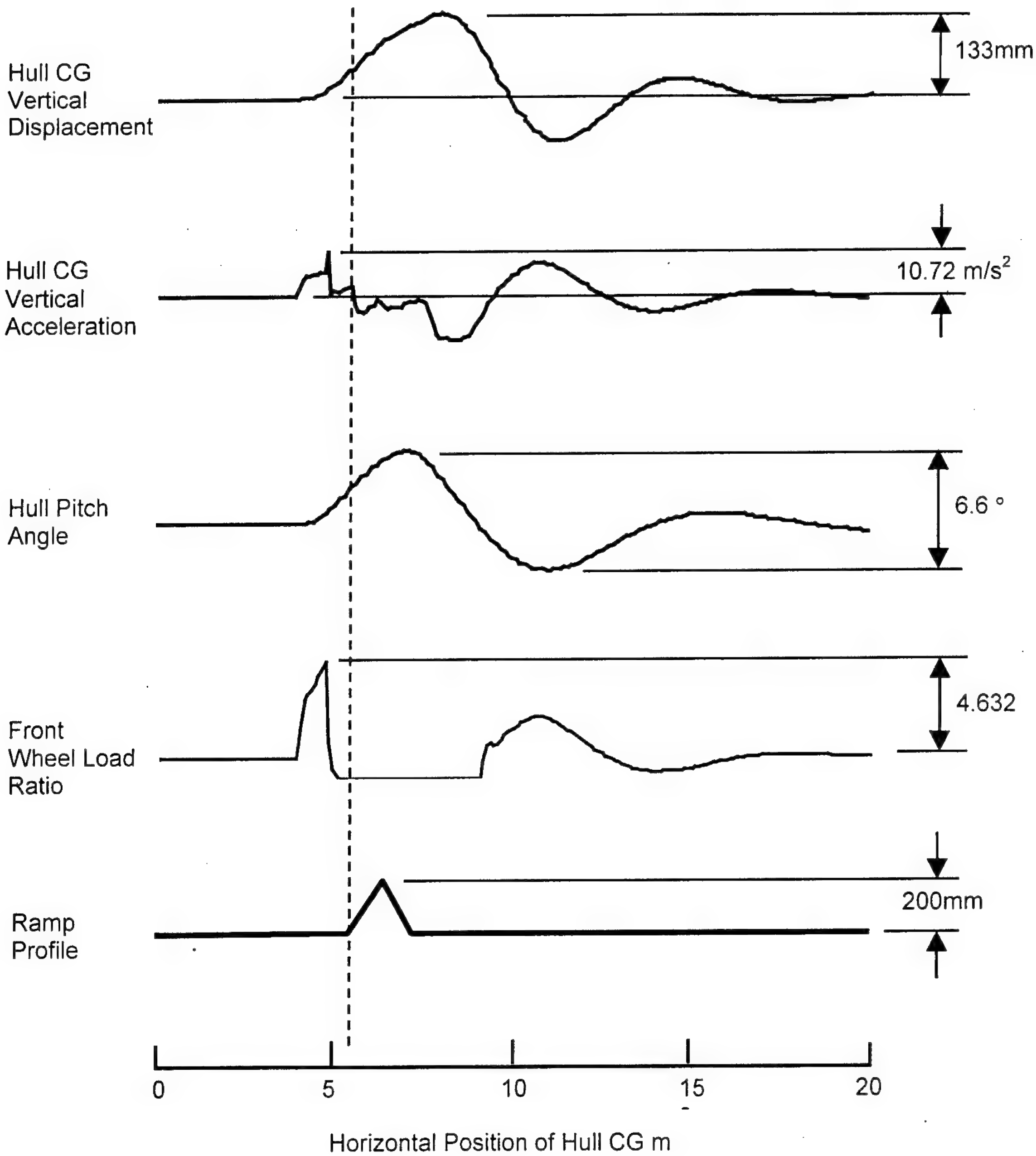


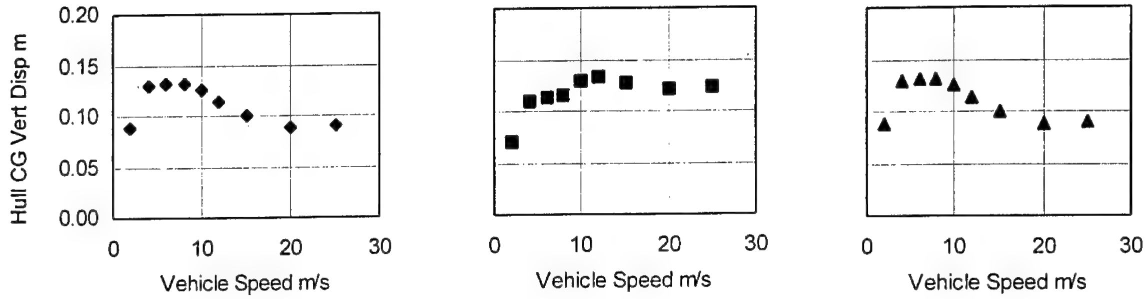
Figure 2-2 Selected Data from TR-1 Traversing Ramp Profile at 10 m/s

For the ramp profile, the vehicle response (Figure 2-2) is of a transient nature hence maximum values are appropriate criteria for suspension performance assessment. The sine wave and random profiles result in quasi steady-state solutions hence the rms value of the hull acceleration, rather than the maximum, has been used. These criteria are presented in Tables 2-1 to 2-3 and Figures 2-3 to 2-5 for each combination of tracked vehicle, terrain and speed. The maximum front wheel load is expressed as a proportion of its static value.

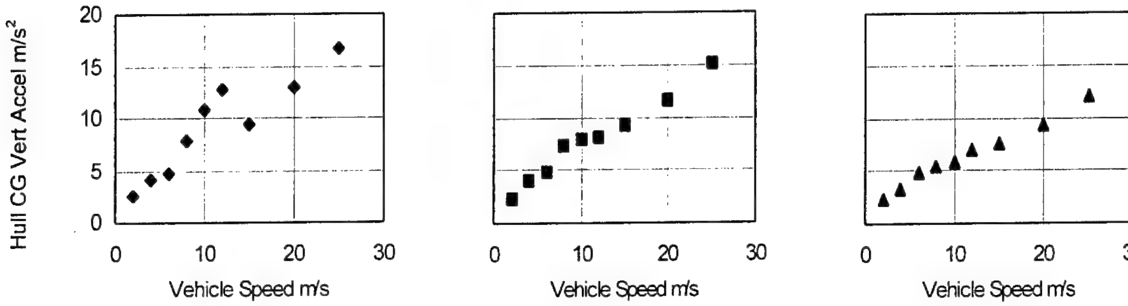
Speed m/s	Vehicle	Hull CG Max Vertical Displ m	Hull CG Max Vertical Accel m/s^2	Max Pitch Range deg	Max Front Wheel Load Ratio
2	TR-1	0.070	2.532	10.9	1.948
	TR-2	0.070	2.354	10.9	1.948
	TR-3	0.089	2.389	11.7	1.876
4	TR-1	0.109	4.167	16.3	3.014
	TR-2	0.109	4.174	16.3	3.015
	TR-3	0.129	3.218	16.4	3.011
6	TR-1	0.114	4.769	12.4	3.656
	TR-2	0.114	4.789	12.4	3.658
	TR-3	0.132	4.801	12.4	3.687
8	TR-1	0.121	7.748	8.4	3.948
	TR-2	0.116	7.317	8.1	3.950
	TR-3	0.131	5.449	7.9	3.852
10	TR-1	0.133	10.720	6.6	4.632
	TR-2	0.130	8.035	6.5	4.634
	TR-3	0.125	5.895	5.7	4.370
12	TR-1	0.139	12.831	5.8	5.050
	TR-2	0.133	8.087	5.6	5.052
	TR-3	0.113	6.908	4.6	4.550
15	TR-1	0.133	9.351	4.9	5.623
	TR-2	0.128	9.353	4.8	5.624
	TR-3	0.100	7.602	3.7	4.440
20	TR-1	0.143	12.881	3.9	6.544
	TR-2	0.122	11.591	4.0	6.550
	TR-3	0.089	9.278	3.0	4.946
25	TR-1	0.171	16.610	3.2	7.333
	TR-2	0.124	15.181	3.4	7.333
	TR-3	0.090	12.132	2.6	5.966

Key: TR-1 = Torsion bar, 200 mm bump travel
TR-2 = Torsion bar, 250 mm bump travel
TR-3 = Hydrogas, 300 mm bump travel

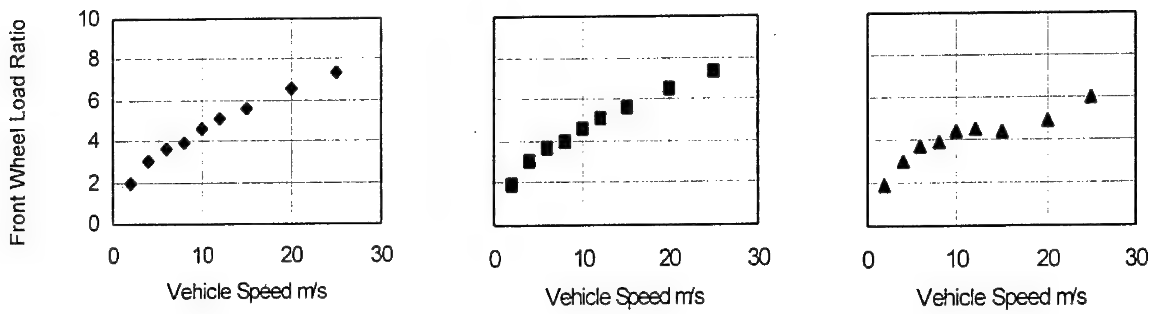
Table 2-1 Results of Tracked Vehicles over Ramp Profile



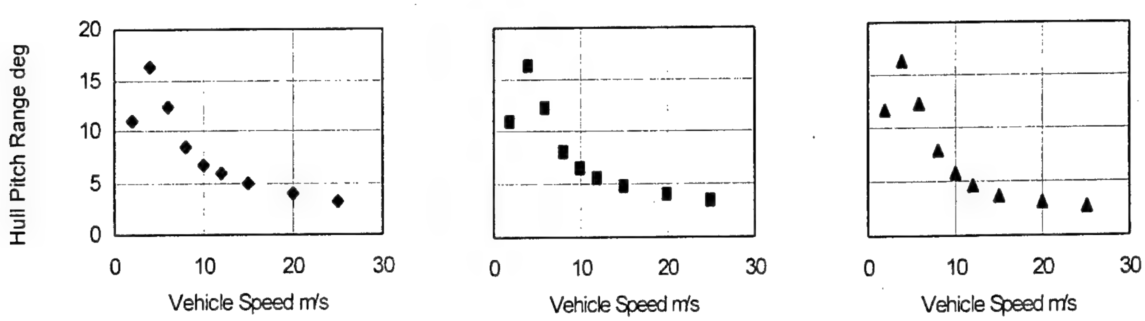
Hull Centre of Gravity Vertical Displacement



Hull Centre of Gravity Vertical Acceleration



Front Road Wheel Load Ratio



Hull Pitch Range

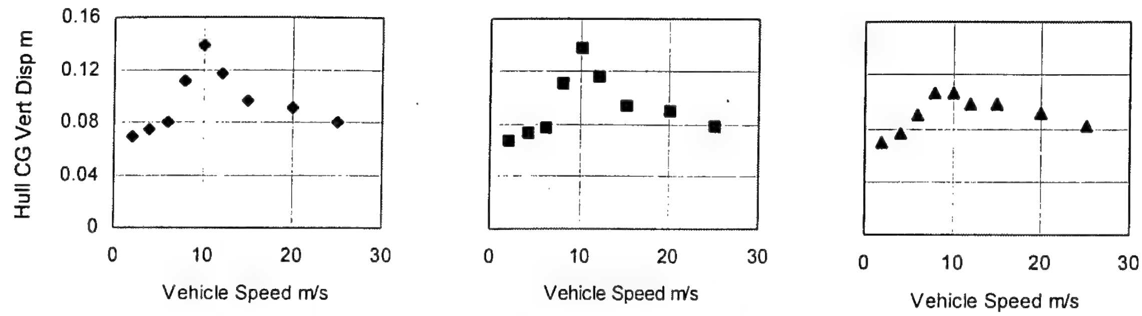
Key: ◆ **TR-1** ■ **TR-2** ▲ **TR-3**

Figure 2-3 – Results of Tracked Vehicles over Ramp Profile

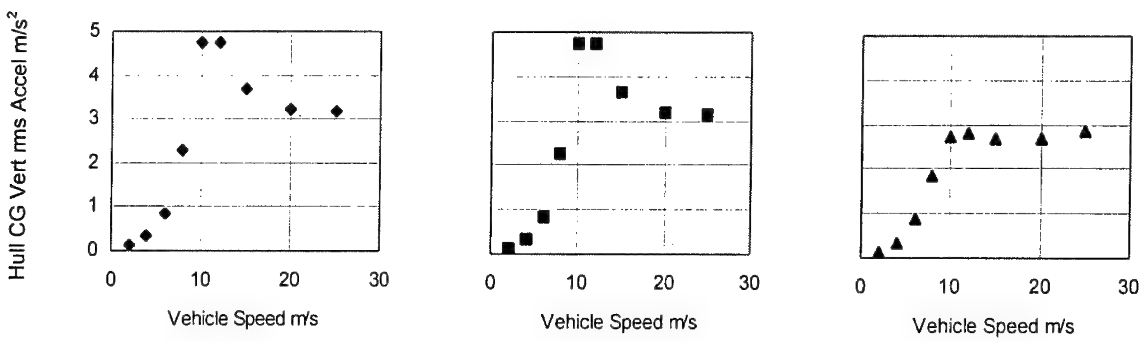
Speed m/s	Vehicle	Hull CG Max Vertical		Max Pitch Range deg	Max Front Wheel Load Ratio
		Displ m	rms Accel m/s^2		
2	TR-1	0.069	0.117	4.6	1.046
	TR-2	0.069	0.115	4.6	1.046
	TR-3	0.070	0.114	4.6	1.045
4	TR-1	0.074	0.333	5.6	1.193
	TR-2	0.074	0.333	5.6	1.193
	TR-3	0.076	0.343	5.7	1.216
6	TR-1	0.080	0.841	7.6	1.607
	TR-2	0.080	0.841	7.6	1.607
	TR-3	0.090	0.869	7.7	1.678
8	TR-1	0.111	2.279	9.2	2.733
	TR-2	0.111	2.281	9.2	2.736
	TR-3	0.107	1.852	7.4	2.247
10	TR-1	0.138	4.726	7.0	2.964
	TR-2	0.138	4.735	7.0	2.968
	TR-3	0.106	2.728	5.9	2.268
12	TR-1	0.117	4.740	5.2	2.697
	TR-2	0.117	4.751	5.2	2.697
	TR-3	0.098	2.809	4.6	2.268
15	TR-1	0.096	3.667	4.0	2.444
	TR-2	0.096	3.672	4.0	2.446
	TR-3	0.098	2.678	3.6	2.038
20	TR-1	0.091	3.211	3.5	2.074
	TR-2	0.091	3.214	3.5	2.075
	TR-3	0.092	2.706	3.5	2.129
25	TR-1	0.080	3.165	3.0	2.196
	TR-2	0.080	3.168	3.0	2.197
	TR-3	0.082	2.845	2.9	2.098

Key: TR-1 = Torsion bar, 200 mm bump travel
TR-2 = Torsion bar, 250 mm bump travel
TR-3 = Hydrogas, 300 mm bump travel

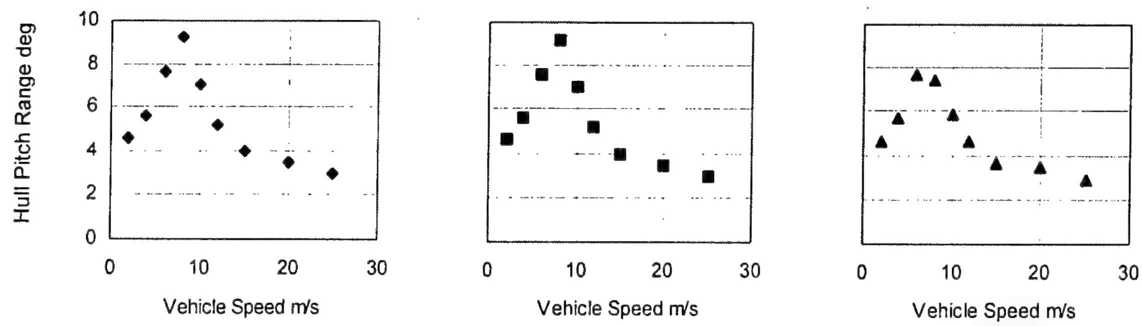
Table 2-2 Results of Tracked Vehicles over Sine Wave Profile



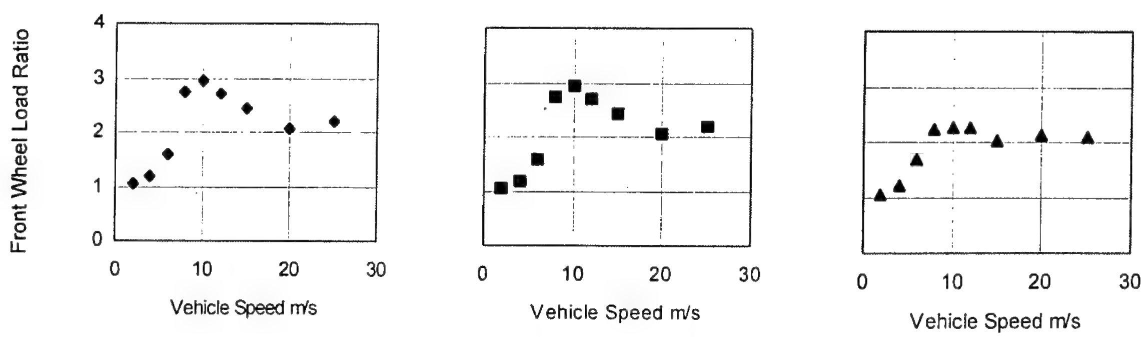
Hull Centre of Gravity Vertical Displacement



Hull Centre of Gravity Vertical rms Acceleration



Hull Pitch Range



Front Road Wheel Load Ratio

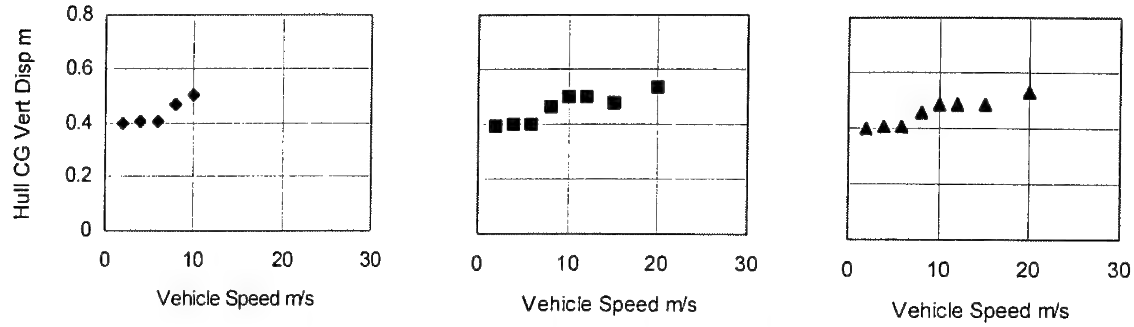
Key: ◆ **TR-1** ■ **TR-2** ▲ **TR-3**

Figure 2.4 Results of Tracked Vehicles over Sine Wave Profile

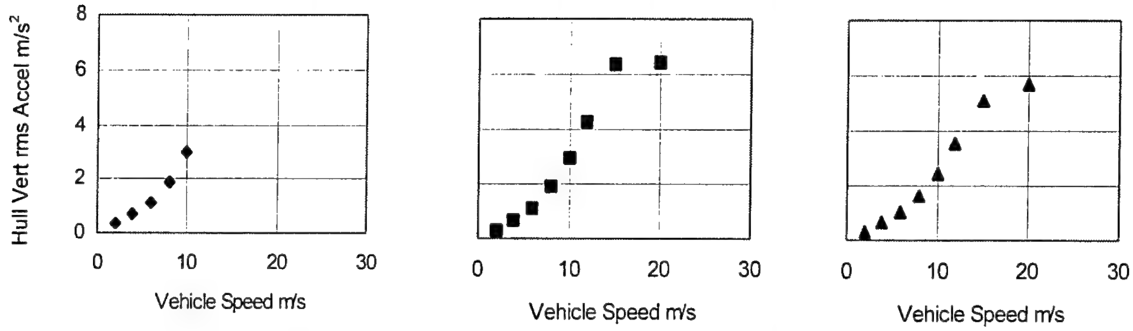
Speed m/s	Vehicle	Hull CG Max Vertical		Max Pitch Range deg	Max Front Wheel Load Ratio
		Displ m	rms Accel m/s^2		
2	TR-1	0.395	0.325	10.0	1.384
	TR-2	0.395	0.323	10.0	1.385
	TR-3	0.398	0.310	10.0	1.374
4	TR-1	0.402	0.692	11.3	1.743
	TR-2	0.402	0.692	11.3	1.743
	TR-3	0.405	0.681	11.3	1.733
6	TR-1	0.402	1.108	14.0	2.450
	TR-2	0.402	1.109	14.0	2.449
	TR-3	0.408	1.045	13.1	2.236
8	TR-1	0.465	1.906	14.1	2.871
	TR-2	0.465	1.908	14.1	2.874
	TR-3	0.460	1.612	13.3	2.728
10	TR-1	0.499	2.972	13.3	3.302
	TR-2	0.499	2.975	13.4	3.302
	TR-3	0.486	2.425	12.6	3.182
12	TR-1	Too	severe		
	TR-2	0.498	4.264	12.4	4.451
	TR-3	0.489	3.584	11.9	3.654
15	TR-1	Too	severe		
	TR-2	0.480	6.364	13.0	3.625
	TR-3	0.488	5.076	12.0	3.341
20	TR-1	Too	severe		
	TR-2	0.533	6.419	16.7	4.792
	TR-3	0.526	5.718	13.2	4.458
25	TR-1	Too	severe		
	TR-2	Too	severe		
	TR-3	Too	severe		

Key: TR-1 = Torsion bar, 200 mm bump travel
TR-2 = Torsion bar, 250 mm bump travel
TR-3 = Hydrogas, 300 mm bump travel

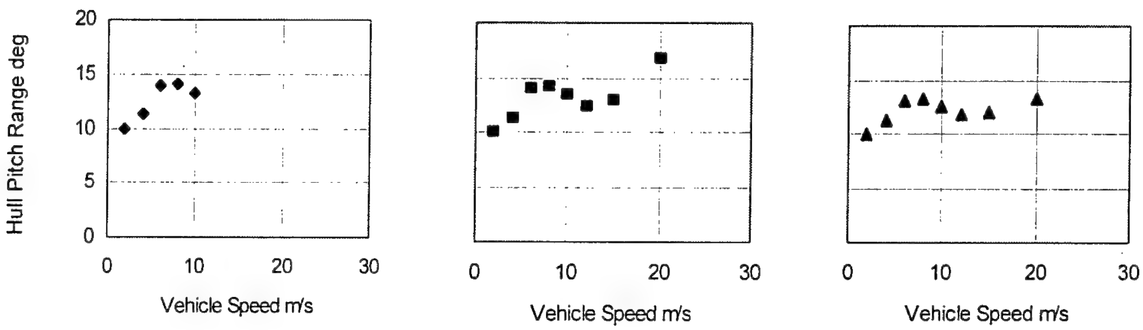
Table 2-3 Results of Tracked Vehicles over Random Profile



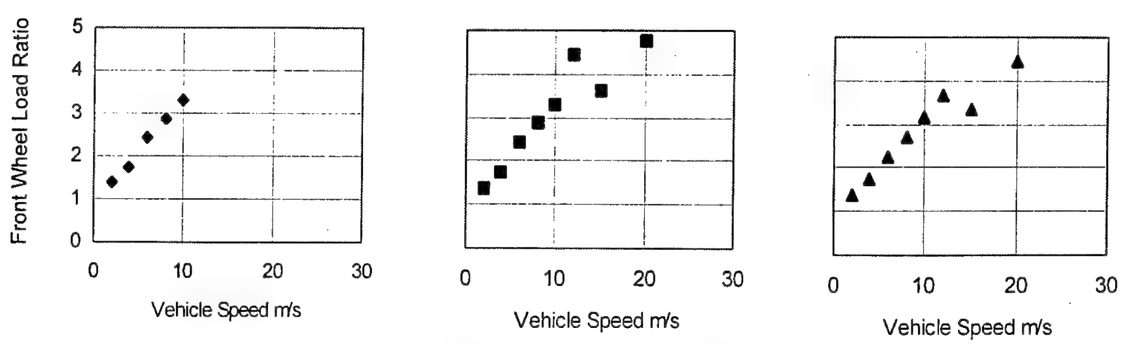
Hull Centre of Gravity Vertical Displacement



Hull Centre of Gravity Vertical rms Acceleration



Hull Pitch Range



Front Road Wheel Load Ratio

Key: ◆ **TR-1** ■ **TR-2** ▲ **TR-3**

Figure 2-5 – Results of Tracked Vehicles over Random Profile

2.2.6 Wheeled Vehicle Suspension Performance Results

A selection of the data from the wheeled vehicle model has been analysed in the same manner as for the tracked vehicle results, and is presented in Tables 2-4 to 2-6 and Figures 2-6 to 2-8. The maximum front wheel load is expressed as a fraction of the appropriate static value.

Speed m/s	Vehicle	Hull CG Max Vertical Displ m	Hull CG Max Vertical Accel m/s^2	Pitch Range deg	Max Front Wheel Load Ratio
2	WH-1	0.061	1.949	4.4	2.027
	WH-2	0.088	4.344	5.0	1.892
	WH-3	0.084	2.752	5.3	2.032
4	WH-1	0.058	3.387	7.3	2.621
	WH-2	0.088	7.923	10.0	2.424
	WH-3	0.097	8.094	9.6	2.875
6	WH-1	0.057	3.817	8.1	3.060
	WH-2	0.075	7.545	8.5	2.898
	WH-3	0.076	8.667	7.9	3.495
8	WH-1	0.062	5.167	7.4	3.427
	WH-2	0.064	7.987	7.7	3.372
	WH-3	0.065	7.827	7.7	4.017
10	WH-1	0.064	6.214	6.3	3.838
	WH-2	0.066	8.123	6.7	3.693
	WH-3	0.057	8.100	6.7	4.405
12	WH-1	0.067	6.740	5.4	4.041
	WH-2	0.067	8.759	6.0	3.885
	WH-3	0.066	8.760	6.3	4.738
15	WH-1	0.071	7.298	4.3	4.173
	WH-2	0.070	9.001	4.8	4.376
	WH-3	0.075	9.151	5.6	5.048
20	WH-1	0.069	7.170	3.0	4.790
	WH-2	0.069	9.293	3.4	4.541
	WH-3	0.075	8.910	4.5	5.413
25	WH-1	0.062	7.471	2.2	4.589
	WH-2	0.062	8.802	2.5	4.279
	WH-3	0.068	8.862	3.4	5.315

Key: WH-1 = Four equally spaced axles, 200 mm bump travel
WH-2 = Three equally spaced axles, 200 mm bump travel
WH-3 = Three axles, close coupled at rear, 200 mm bump travel

Table 2-4 Results of Wheeled Vehicles over Ramp Profile

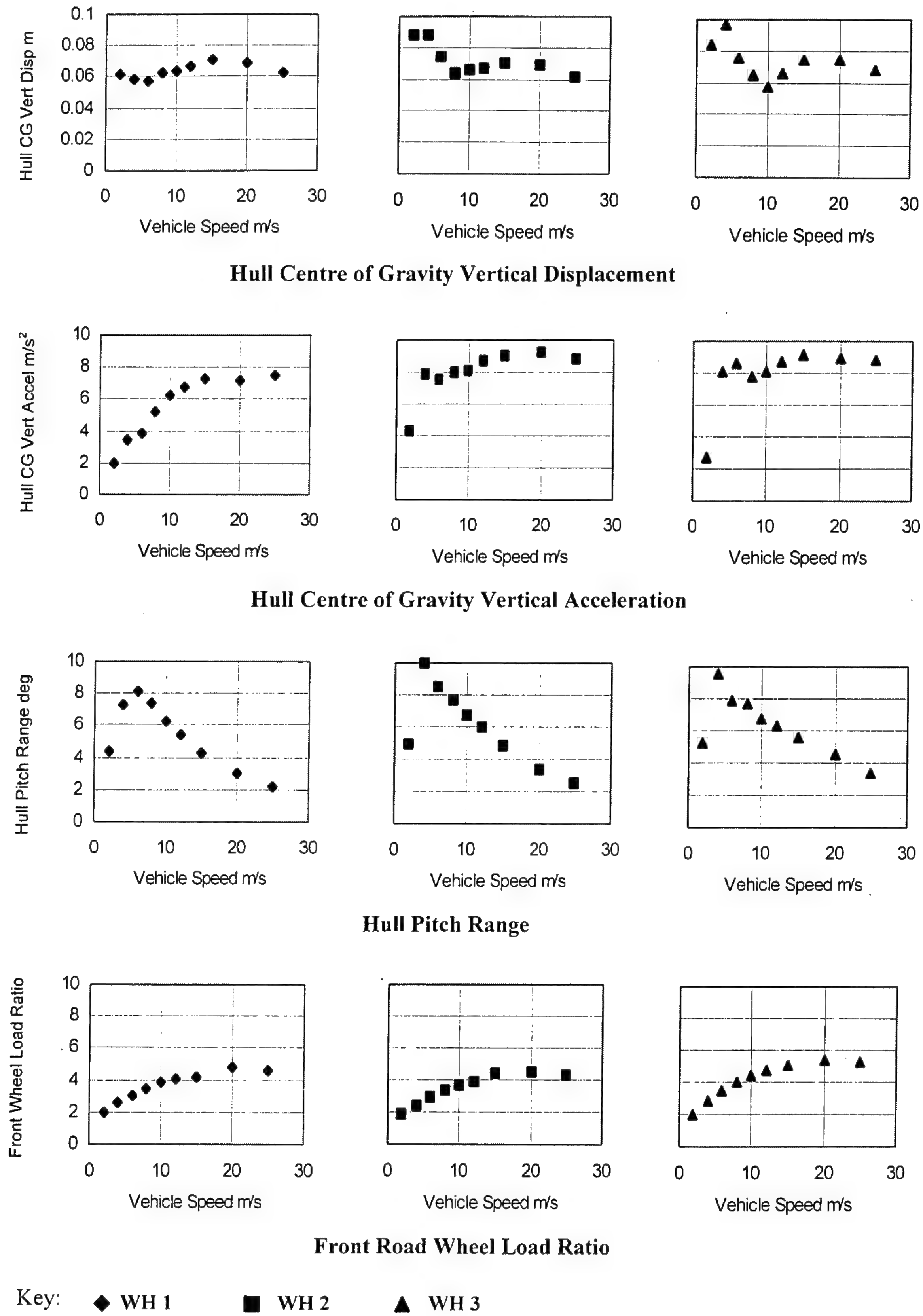
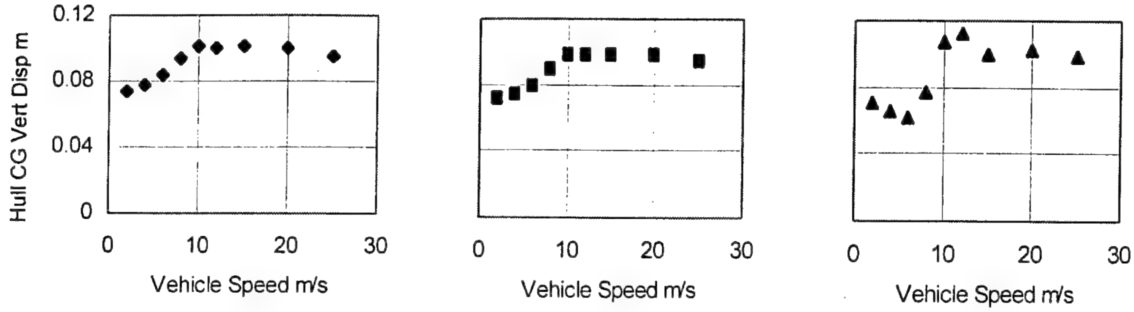


Figure 2-6 – Results of Wheeled Vehicles over Ramp Profile

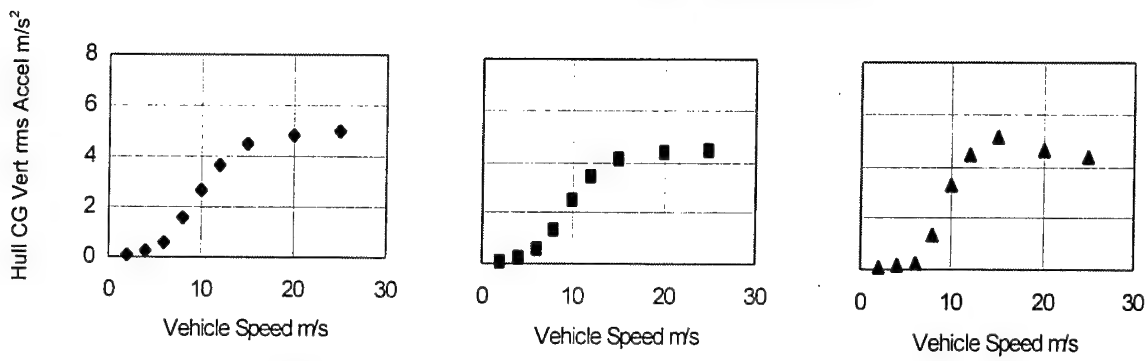
Speed m/s	Vehicle	Hull CG Max Vertical		Max Pitch Range deg	Max Front Wheel Load Ratio
		Displ m	rms Accel m/s^2		
2	WH-1	0.074	0.066	3.8	1.334
	WH-2	0.072	0.057	3.7	1.283
	WH-3	0.071	0.063	3.8	1.387
4	WH-1	0.077	0.241	4.7	1.596
	WH-2	0.074	0.219	4.5	1.517
	WH-3	0.066	0.160	4.4	1.692
6	WH-1	0.084	0.624	6.7	2.000
	WH-2	0.080	0.559	6.1	1.850
	WH-3	0.062	0.265	5.5	2.040
8	WH-1	0.094	1.594	8.8	2.382
	WH-2	0.090	1.350	8.3	2.227
	WH-3	0.077	1.327	7.0	2.518
10	WH-1	0.101	2.642	8.8	2.350
	WH-2	0.098	2.517	8.7	2.340
	WH-3	0.107	3.256	7.5	2.772
12	WH-1	0.100	3.678	7.2	2.232
	WH-2	0.098	3.466	7.7	2.238
	WH-3	0.112	4.459	7.2	2.874
15	WH-1	0.101	4.472	5.3	2.028
	WH-2	0.099	4.129	5.8	2.040
	WH-3	0.100	5.102	6.0	2.616
20	WH-1	0.100	4.849	3.3	1.937
	WH-2	0.098	4.393	3.8	1.918
	WH-3	0.102	4.612	4.5	2.284
25	WH-1	0.095	4.975	2.8	2.090
	WH-2	0.095	4.461	3.1	2.043
	WH-3	0.099	4.410	3.9	2.449

Key: WH-1 = Four equally spaced axles, 200mm bump travel
WH-2 = Three equally spaced axles, 200 mm bump travel
WH-3 = Three axles, close coupled at rear, 200 mm bump travel

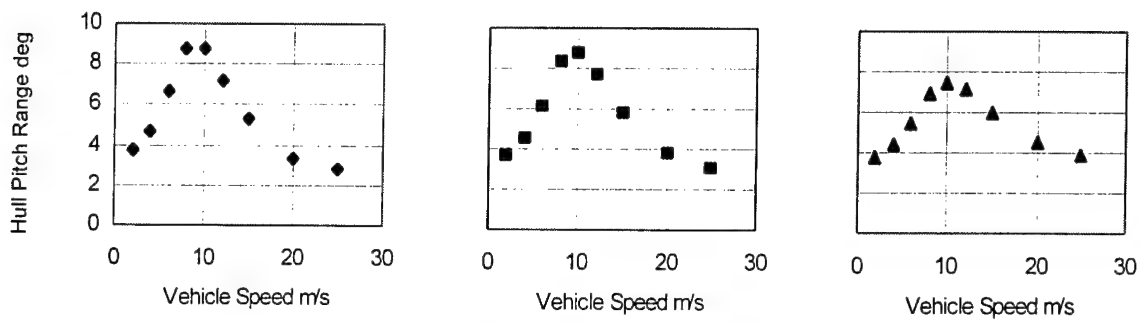
Table 2-5 Results of Wheeled Vehicles over Sine Wave Profile



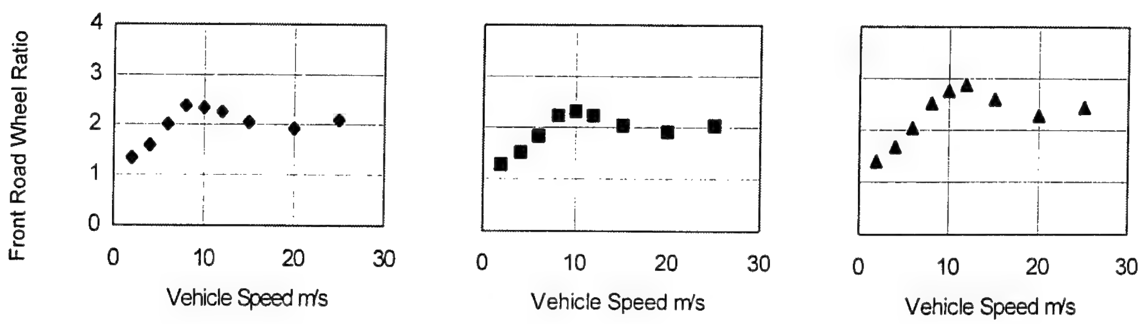
Hull Centre of Gravity Vertical Displacement



Hull Centre of Gravity Vertical rms Acceleration



Hull Pitch Range



Front Road Wheel Load Ratio

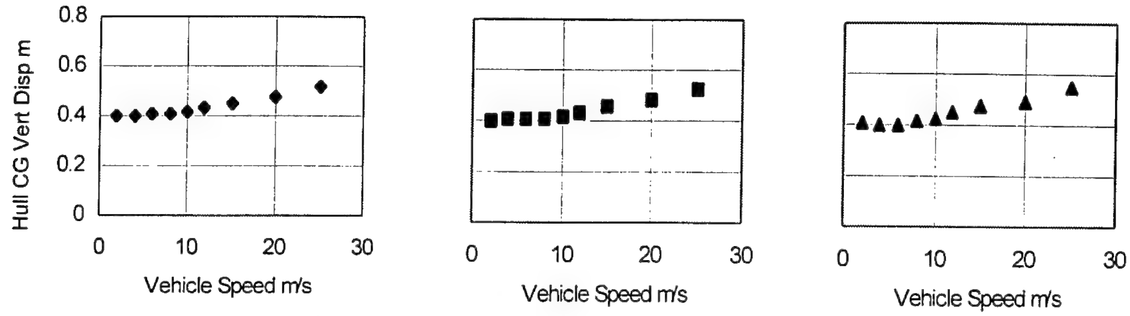
Key: ◆ WH 1 ■ WH 2 ▲ WH 3

Figure 2-7 – Results of Wheeled Vehicles over Sine Wave Profile

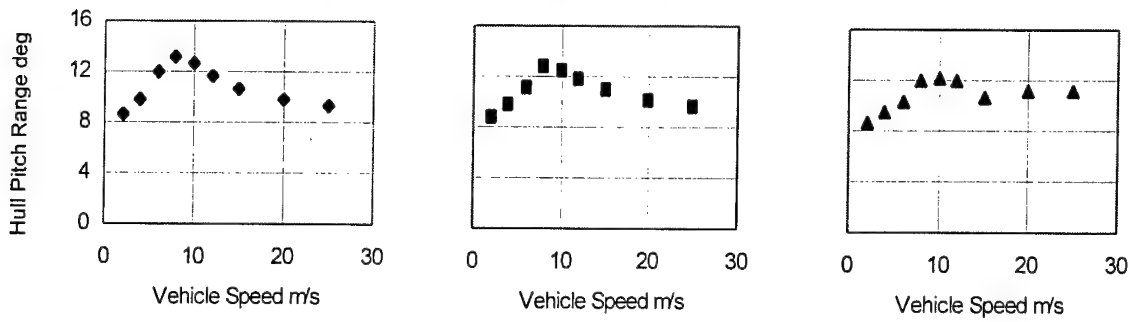
Speed m/s	Vehicle	Hull CG Max Vertical Displ m	Hull CG Max Vertical rms Accel m/s^2	Max Pitch Range deg	Max Front Wheel Load Ratio
2	WH-1	0.402	0.498	8.7	1.725
	WH-2	0.403	0.573	8.8	1.713
	WH-3	0.408	0.600	8.7	1.919
4	WH-1	0.404	0.667	9.9	1.913
	WH-2	0.406	1.007	9.8	1.976
	WH-3	0.401	1.064	9.5	2.245
6	WH-1	0.406	0.910	12.0	2.596
	WH-2	0.407	1.199	11.2	2.374
	WH-3	0.401	1.324	10.3	2.614
8	WH-1	0.409	1.361	13.1	2.985
	WH-2	0.408	1.485	12.9	2.830
	WH-3	0.413	1.779	12.0	3.504
10	WH-1	0.413	2.122	12.6	3.108
	WH-2	0.413	2.106	12.5	3.010
	WH-3	0.426	2.548	12.1	3.878
12	WH-1	0.432	3.087	11.6	3.223
	WH-2	0.435	3.046	11.9	3.177
	WH-3	0.449	3.551	12.0	4.537
15	WH-1	0.453	4.651	10.7	3.245
	WH-2	0.458	4.632	11.0	3.237
	WH-3	0.479	5.339	10.7	4.211
20	WH-1	0.479	6.670	9.8	4.007
	WH-2	0.485	6.636	10.1	3.807
	WH-3	0.491	6.943	11.1	4.767
25	WH-1	0.513	7.992	9.3	5.260
	WH-2	0.522	7.967	9.6	4.900
	WH-3	0.551	8.182	11.2	6.616

Key: WH-1 = Four equally spaced axles, 200 mm bump travel
WH-2 = Three equally spaced axles, 200 mm bump travel
WH-3 = Three axles, close coupled at rear, 200 mm bump travel

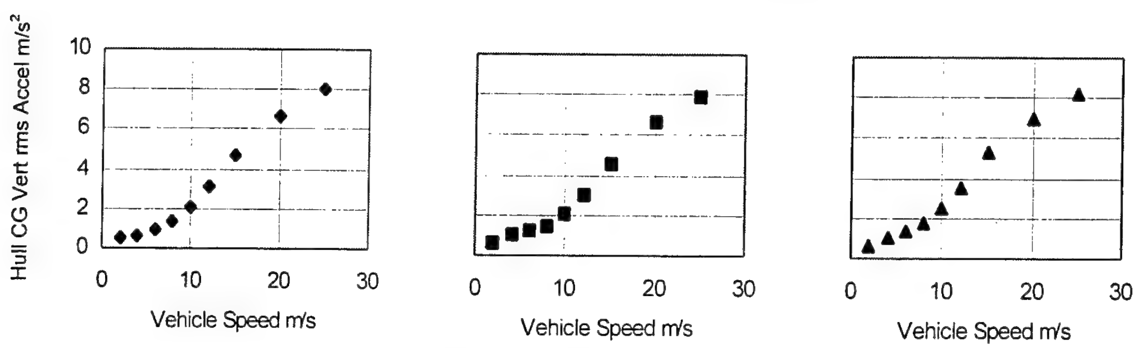
Table 2-6 Results of Wheeled Vehicles over Random Profile



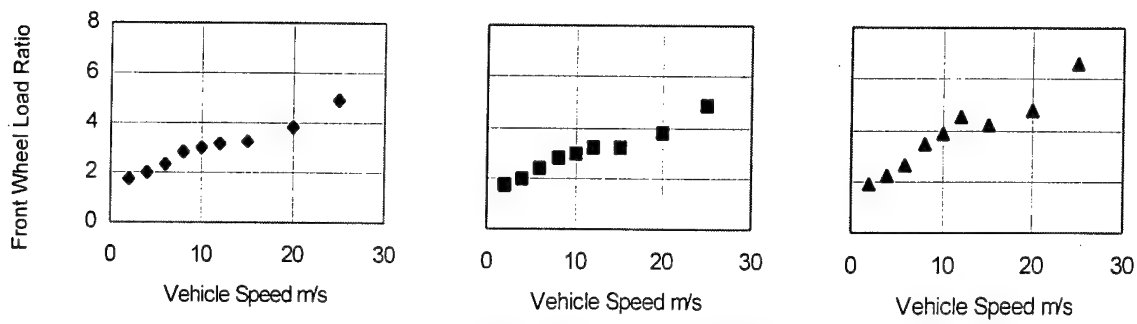
Hull Centre of Gravity Vertical Displacement



Hull Centre of Gravity rms Acceleration



Hull Pitch Range



Front Road Wheel Load Ratio

Key: ◆ **WH 1** ■ **WH 2** ▲ **WH 3**

Figure 2-8 – Results of Wheeled Vehicles over Random Profile

2.2.7 Discussion of Suspension Modelling Results

Any vehicle suspension and geometry can be optimised for a particular speed and terrain, disguising its vulnerability to other operating conditions. By choosing three very different terrain profiles, and a range of speed that amply covers any realistic scenario, a more balanced picture emerges. Some aspects of the results obtained from the model, and the effects that the vehicle and terrain data have on these results, are discussed in the remainder of this section.

The nature of the vehicle response to terrain is discontinuous. Contact between the vehicle and the ground occurs over relatively small discreet areas, and as the vehicle speed varies these contact points change. For example, in Figure 2.2, the front wheel load ratio has a constant zero value for a finite time shortly after the wheel has cleared the ramp, indicating that the wheel has lost contact with the ground. Similar effects occur with the sine wave and random profiles and, at specific speeds, a road wheel may just miss contact with a peak on the terrain that, at a higher or lower speed, may result in a hard impact. This effect can be seen in Figure 2-5 for the front wheel load ratio with TR-2 and TR-3. With TR-1 this effect was so great that the front road wheel struck an upward sloping section of terrain almost perpendicularly whilst the arm was on its bump stop. This brought the vehicle to an abrupt stop and the run was described as "too severe" (see Table 2.3). Further discontinuities occur due to bump stop contact. For these reasons no attempt has been made to draw curves through the data points shown in Figures 2-3 to 2-8. Although trends are frequently evident, the data should be interpolated with care.

The model assumes the profile is rigid, any compliance being confined to the vehicle wheels and suspension. Most real terrain will have some degree of compliance. Although this is difficult to quantify, the effect will be to moderate the vehicle response, giving results less severe than those described.

The hull displacement, acceleration (maximum or rms, as appropriate) and pitch range are indicative of the quality of the ride. Some of the values obtained are quite high and might well be considered unacceptable. For the tracked vehicles on the ramp profile, maximum acceleration values significantly in excess of 1 g occur, albeit for very short durations. It is unlikely that a vehicle driver would deliberately subject himself, and the remainder of the crew, to such exposure but a hidden obstacle such as a boulder or tree stump might well result in accelerations of this magnitude. It is interesting to note that the wheeled vehicles performed rather better over the ramp profile. This may be due in part to the effective increase in wheel travel due to the tyres, and the greater wheel spacing, allowing one wheel to pass clear of the ramp before the next wheel makes first contact. For the sine wave profile maximum acceleration values are in excess of 0.5 g rms. This would be considered a very severe ride, especially if the condition prevailed for more than a short while. The tracked vehicles experienced marginally lower rms accelerations and pitch motion, especially at the higher speeds, than the wheeled vehicles on the sine wave profile, possibly due to the "bridging" effect of the track and greater number of road wheels. Similar effects can be seen over the random profile, except for the special case with the tracked vehicles described earlier as "too severe". It should be noted that the relatively high vertical displacement of the hull follows because the random profile has a positive rather than a zero mean value, see Annex 2C. This is also true, but to a lesser extent, of the sine wave profile.

The maximum front road wheel load ratio is a measure of the suspension loads, and the likelihood of damage occurring. As might be expected, these values tend to follow the same trends shown by the hull accelerations, and would probably be considered unacceptable in some cases. Load ratio differences between the tracked and wheeled vehicles appear to be small. Differences between the three tracked vehicles are also small until the combination of speed and terrain results in hard bump stop contact, and this is discussed later. For the wheeled vehicles, WH-2 with the three equally spaced axles performs consistently a little better than WH-1 with four axles. This is probably a feature of the tyre stiffnesses chosen, and may therefore not be significant. When the axles are

close coupled at the rear the front axle is relatively lightly loaded and this will naturally lead to higher load ratios.

A large wheel travel before bump stop contact is self evidently a good feature of any off-road vehicle suspension. With TR-1 and TR-2 the only difference is in the bump travel (200 and 250 mm respectively) and if no bump stop contact occurs both vehicles will give identical results. In most cases some bump stop contact did occur, but only lightly at the lower speeds, and the similarity between such cases is clearly seen in Tables 2.1 to 2.3. Even TR-3 with its 300 mm travel shows little improvement at the lower speeds where its hardening spring characteristic is only marginally exploited. However, at higher speeds, the advantages of the greater bump travel and hardening characteristic become increasing more evident. In the model it is relatively easy to increase bump travel, but this may not be so easy in practice without compromise. A 200 mm bump travel could probably be achieved with a single torsion bar. At 250 mm it is likely that a double length bar, for example tube over bar, would be required, increasing the dimensions and hence reducing the internal hull volume for given external dimensions. Furthermore, the maximum bump travel will be limited by the ground clearance, which is a function of road wheel diameter, wheel arm length and wheel arm angle. Wheel diameter, in turn, is related to the number of wheels and the length of the track in ground contact. These parameters interact with mobility through the effect of ground pressure. The wheeled vehicles all had the same 200 mm bump travel. The linkages commonly associated with an independent wheeled suspension, especially if steered and driven, make it difficult to achieve much more than this.

No attempt has been made in this study to examine the effects of different damping characteristics. As a general guide damping should be the minimum necessary to keep the suspension off its bump stop. However, this requires assumptions to be made about the operating conditions of the vehicle.

For both the tracked and wheeled vehicles the same hull mass has been used. The total vehicle masses of the wheeled vehicles will differ slightly from each other, and from the tracked vehicles, reflecting the different running gear arrangements (see Annexes 2A and 2B for details). For vehicles with a significantly greater mass, but of a similar size and configuration, say as a result of additional armour, the suspension characteristics could be chosen such that the model would give a similar response. If the greater mass were due to an increase in vehicle size, perhaps leading to an additional wheel station or axle, the relationship between the hull mass and pitch moment of inertia would change, as would the length of the ground contact base. Both of these effects would probably lead to a reduced pitch response. Converse arguments apply to a vehicle of a lower mass, with the additional constraint that unsprung mass will probably not decrease in the same proportion.

As already described, the suspension geometry of the wheeled vehicles is modelled as a vertical telescopic pillar. There are other suspension types which may reveal results differing in detail, although the general trends will be similar. A particular geometry could be modelled only when it has been specified. By contrast a modern tracked vehicle is almost certain to have trailing arms, as modelled.

2.2.8 Summary of Suspension Performance Modelling

The performance of any particular suspension must be examined at a range of speed and over several profiles. A system that performs well in one situation may perform less well in others.

The behaviour of the suspension is discontinuous. Results should be interpolated with care.

The model takes no account of ground compliance, which would otherwise reduce the severity of the vehicle ride.

The tracked vehicles performed better than the wheeled vehicles at the higher speeds. At lower speeds the reverse is true, although the differences at these lower speeds are small. This applies to both ride, using hull motion as the criterion, and to suspension loads on the front wheel station or axle.

A large bump travel makes a significant contribution to the suspension performance only if the conditions are sufficiently severe that the bump stop would otherwise be struck. The advantages of a large bump travel must be weighed against the complexities that may arise from achieving it. In this study, the larger bump travel suspension also had a hardening characteristic, and it is not easy to identify the contribution made by each of these two features.

The effect of changing the damping characteristic has not been examined.

The vehicle mass is approximately constant for all vehicle variants considered. With some minor limitations, the results obtained will also apply to vehicles of greater or lesser mass which have similar natural frequencies and damping ratios.

2.3 AUTOMOTIVE PERFORMANCE

The effect of the power train parameters on the vehicle performance has been investigated using a computer simulation to predict the time to maximum speed on modest off-road going, and the gradient capability. Three different transmission systems were modelled, namely, a manual stepped-ratio gearbox with a friction clutch, an automatic stepped-ratio gearbox with a torque converter, and a continuously variable transmission (CVT). The same engine characteristics have been used in all cases. The model is not specific to either a tracked or a wheeled vehicle, but the data has been biased towards a tracked vehicle. It is recognised that parameters such as road load and gear ratios are likely to be dependent on the particular vehicle and running gear chosen.

2.3.1 Power Train Model

The model comprises a prime mover, a main coupling, a main speed-change ratio, a final-drive ratio, and a vehicle mass. Engine auxiliaries, for example, cooling fans and an electrical generator can be included, and also output auxiliaries such as a power take off or hydraulic pump (see Annex 2D, Figure 2D.1)

The engine is modelled as a torque-speed characteristic with a stall line, maximum and minimum fuel limits, and a governor run-out line. The engine response to a change in fuel demand is assumed to follow an exponential law. Although a diesel engine is envisaged, any prime mover that can be described in similar terms can be used. The auxiliaries and vehicle road-load are defined in terms of their load-speed characteristics.

The friction clutch is defined by its engaging characteristic and its torque capacity. Lock-up is deemed to occur when the slip speed is less than some threshold value, and slip to occur when the transmitted torque would otherwise exceed the current value of the torque capacity.

The torque converter is defined by the speed-ratio vs torque-ratio characteristic, and the normalised output-torque vs speed-ratio characteristic. Lock-up can be set to occur in the higher gears at some slip threshold.

The CVT is assumed to give a torque output corresponding to the maximum engine power. This characteristic is limited at the low speed end by a maximum torque chosen to be consistent with the available traction, and at the high speed end by the maximum engine speed. No particular form of CVT has been assumed although it is envisaged that an electric system would be a strong contender.

2.3.2 Power Train Data

A schematic of the power train is shown in Annex 2D, together with the data used to describe the various systems. A typical engine torque-speed characteristic was chosen to give a vehicle power-mass ratio of about 18 kW/tonne. Allowing for the various system losses and auxiliaries, this gives a maximum speed of approximately 70 km/h (19.2 m/s) on flat terrain against the specified external resistance.

For the manual change with friction clutch transmission, six forward gears were chosen, whilst for the automatic change with torque converter this was reduced to four. For both stepped ratio transmissions the overall ratio in low, including the effect of the final drive and wheel/sprocket diameter has been selected so that, the vehicle can just climb a 30° (58% tangent) gradient using the maximum available torque. This overall ratio has been achieved by a combination of the main speed-change ratio, final-drive ratio and wheel/sprocket diameter as shown in Annex 2D.

2.3.3 Automotive Performance Results

A range of data is available from the model. A typical selection is shown in Figure 2.9.

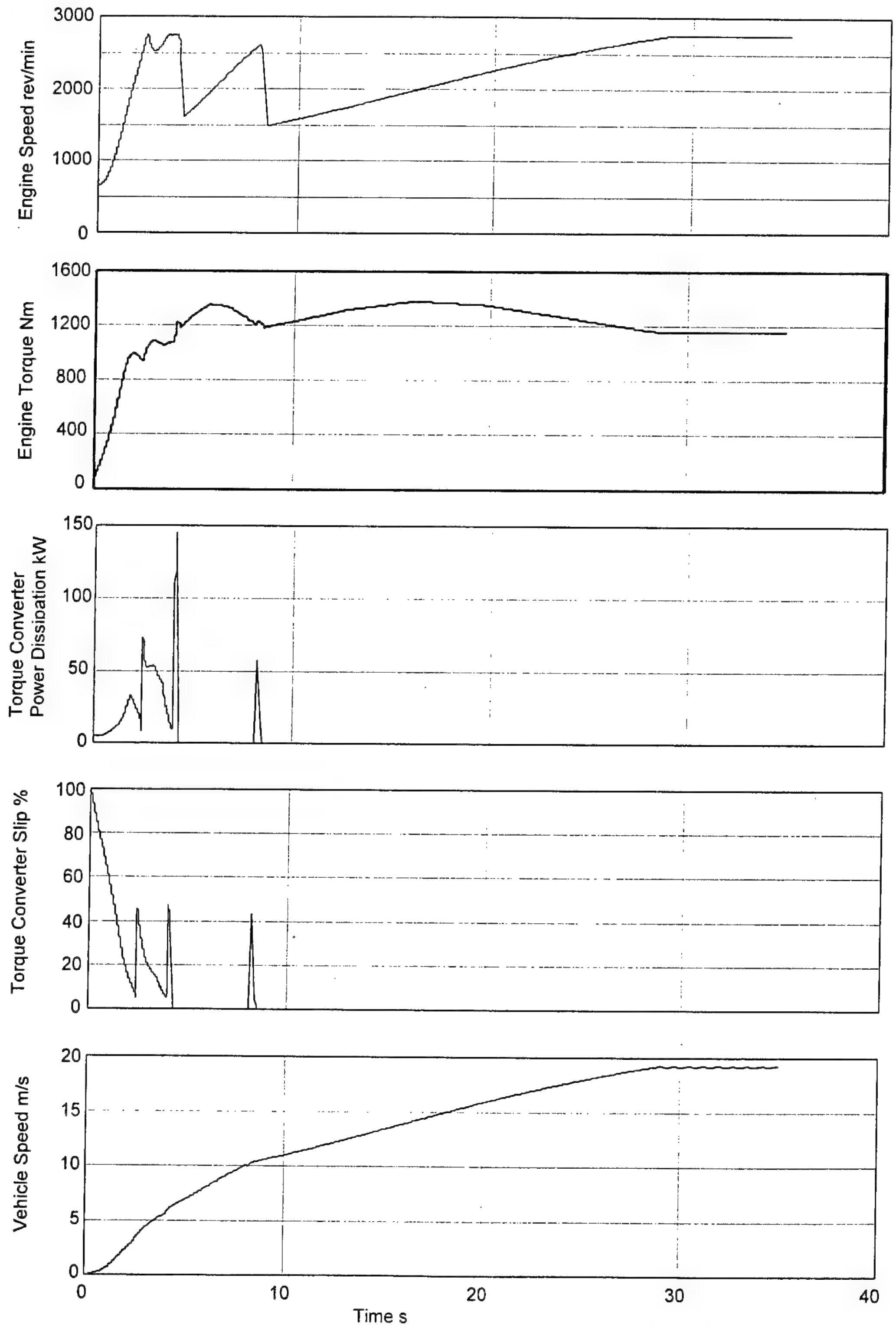
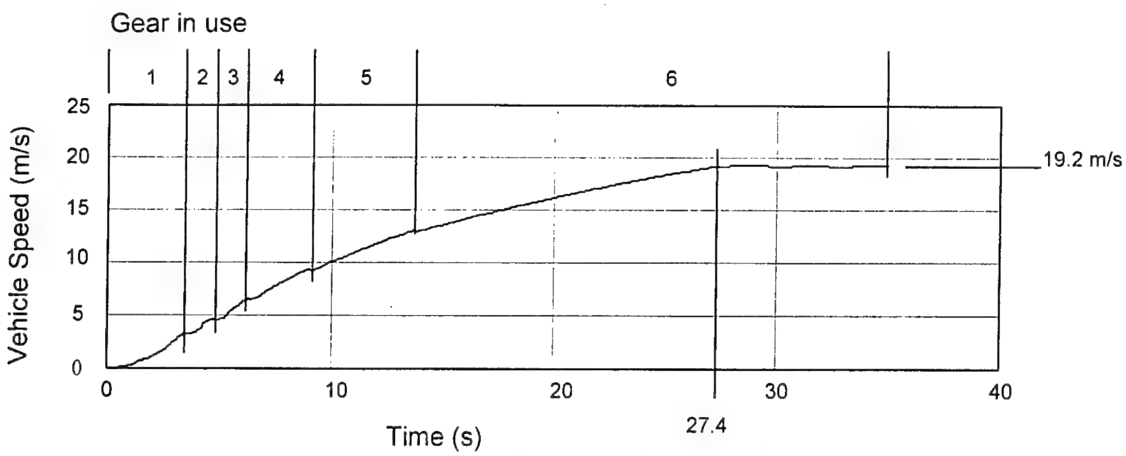
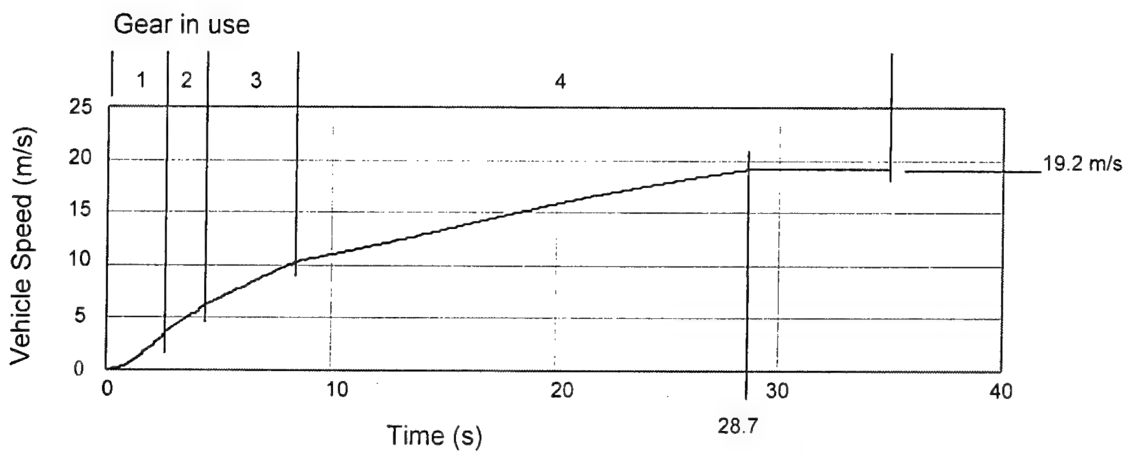


Figure 2.9 Typical Results from Automotive Performance Model Automatic Change with Torque Converter

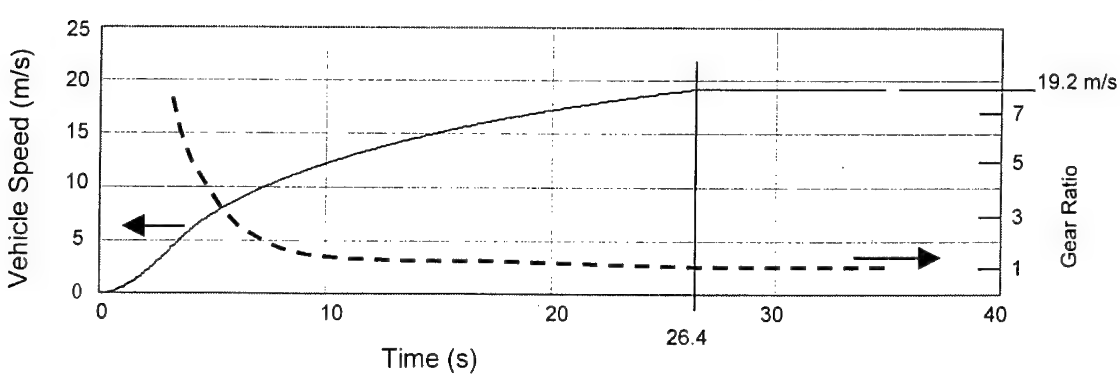
The results of the time to maximum speed for the three transmission types are given in Figure 2-10. For the stepped-ratio changes the gear-in-use is shown along the top of each plot. For the CVT the gear ratio is represented by the dotted line read against the right hand scale.



Manual Change with Friction Clutch and 6 Gears



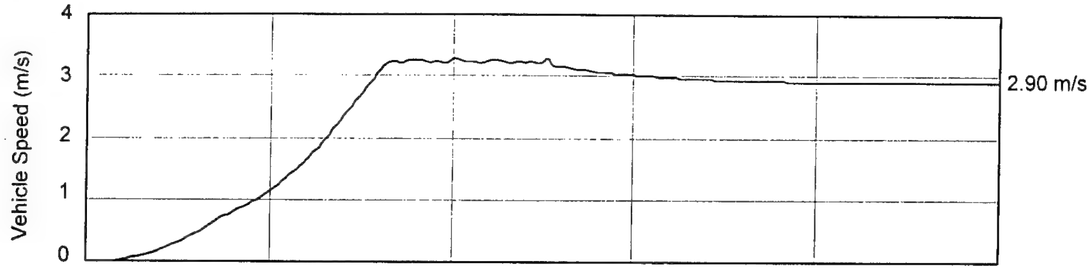
Automatic Change with Torque Converter and 4 Gears



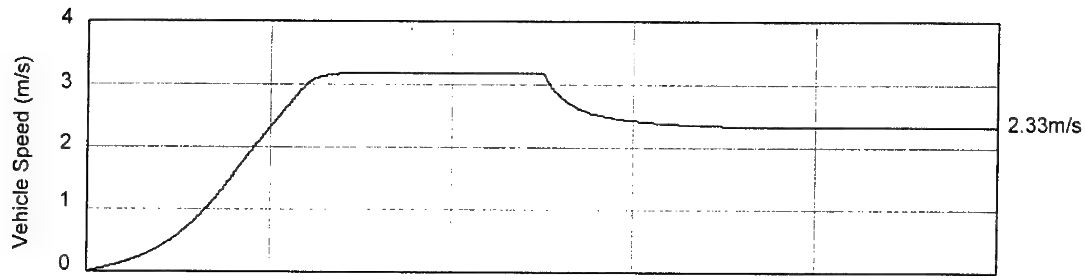
Continuously Variable Transmission

Fig 2-10 Time to Steady State Maximum Speed

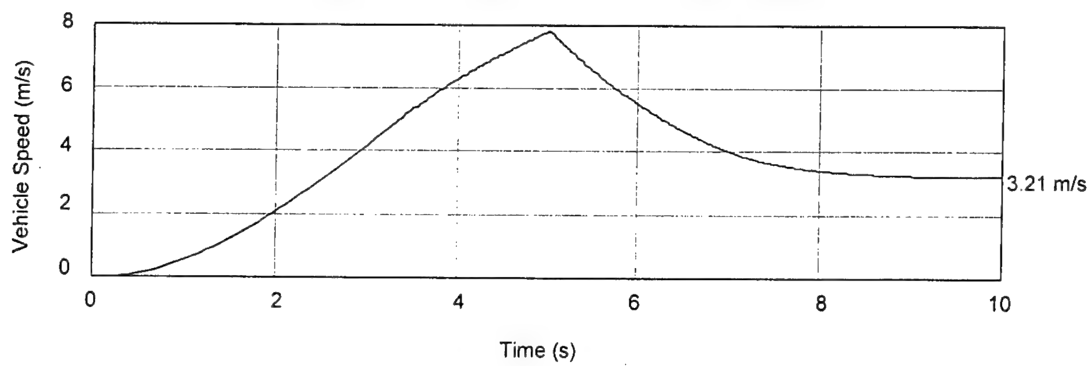
For the gradient capability all vehicles were allowed to accelerate for five seconds on level ground at maximum fuel condition before encountering the gradient. In the case of the two stepped ratio transmissions the vehicles were held in first gear which limited the maximum speed achievable to about 3.2 m/s The CVT did not suffer from this limit and achieved a speed of about 8 m/s. The results of these simulations are shown in Figure 2-11, with the steady-state speed attained shown against the right hand side.



Manual Change with Friction Clutch (First Gear)



Automatic Change with Torque Converter (First Gear)



Continuously Variable Transmission

Fig 2-11 Steady State-Speed on 30° Gradient

2.3.4 Discussion of Automotive Modelling Results

The vehicle with the manual change and friction clutch achieved the maximum speed of 19.2 m/s in 27.4 s, on the level, using all six ratios. Some of the gear changes occur in rapid succession, particularly from 1 to 2 and from 2 to 3. This would require a very high level of driver skill, and may not be achievable consistently in practice. However, it should be noted that these gear change times are comparable to those achieved in some experimental fully automated layshaft transmissions. The vehicle with the automatic change and torque converter took 28.7 s to reach the same speed using all four of its ratios. There are two possible reasons for this slightly increased time. Firstly, the reduced number of ratios means that the engine is operating for longer

periods at lower torques, and secondly, the relatively high losses associated with torque converters when the lower gears are in use against high loads, leading to significant slip. Figure 2-9 shows the slip and power dissipation for this particular case, with the latter reaching values of several tens of kW sustained for several seconds. The CVT shows the shortest time, 26.4 s, to reach the steady state speed. A short time is to be expected here since the system is using the maximum power throughout the whole of the working range. There are circumstances in which the ability to operate at the optimum gear ratio without driver intervention can be particularly advantageous. However, it must be remembered that the efficiency of a rear CVT will vary widely dependent on its type and operating condition, and hence whilst the results of this investigation may be taken as typical, they should not be treated as general.

The differences in the times to reach the steady-state speed are small for the data used, and arguably of little practical importance. It is unlikely that credible changes could be made to the data to change this conclusion, although for other situations the differences may be more significant.

The lowest gear with the stepped ratio transmissions was chosen, in conjunction with the final drive and wheel sprocket diameter, so that the engine had the capability to take the vehicle up a 30° gradient, and this is seen in Figure 2-11. The vehicle with the manual change and friction clutch achieved a steady state speed of 2.90 m/s compared with 2.33 m/s for the vehicle with the automatic change and torque converter. This difference also follows from the higher losses associated with the torque converter, about 63 kW in this case, which has design implications for the cooling system. The vehicle with the CVT performed rather better, with a steady state speed of 3.21 m/s, as expected due to the engine operating on a more favourable part of its characteristic.

Situations can be envisaged where the benefit of a CVT is even greater, for example, if the resistance is such that a stepped-ratio gearbox just fails to hold a particular gear, and has to operate in the next lower gear at maximum engine speed, then the vehicle speed penalty may be severe.

2.3.5 Summary of Automotive Performance Modelling

Whilst factors such as road load and losses might differ between tracked and wheeled vehicles, the nature of the findings are applicable to both.

The differences between the three transmission types modelled has only a marginal effect on the time to reach a steady speed on a flat level road, although the manual change with friction clutch would require a high level of driver skill to realise the result predicted by the model.

Differences on the gradient climbing ability are a little greater, with the CVT performing rather better than the manual change with friction clutch, which, in turn, was rather better than the automatic change with the torque converter.

These findings are subject to the assumptions made regarding efficiencies, gear ratios, torque converter characteristics, CVT characteristics, and on other possible factors.

The relative performance of the three types of transmission may differ when tested against different going conditions.

ANNEX 2A – TRACKED VEHICLE DATA

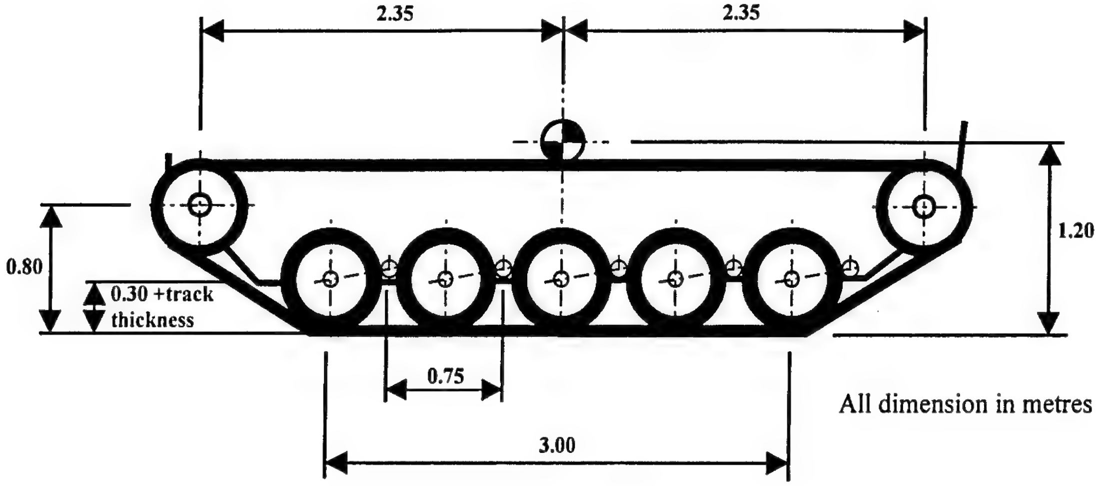


Figure 2A.1 – Layout and Common Dimensions of Tracked Variants

Other Common Data

Hull mass (kg)	15000
Hull pitch moment of inertia (kg m^2)	30000
Road wheel mass (kg)	35
Road wheel moment of inertia about wheel arm axis (kg m^2)	6
Wheel arm mass (kg)	40
Wheel arm moment of inertia about wheel arm pivot (kg m^2)	3.5
Mass factor equivalent of rotating parts	1.2
Wheel arm length (m)	0.4
Wheel arm static angle (deg)	10
Road wheel diameter (m)	0.6

CG to wheel arm centres (m):

Station	Horizontal	Vertical
1	1.894	-0.780
2	1.144	-0.780
3	0.394	-0.780
4	-0.356	-0.780
5	-0.106	-0.780

Track characteristic length (m)	4.792
Track longitudinal stiffness index	4
Fitted track tension (N)	12000
Road wheel tyre radial stiffness (N/m)	10^6
Road wheel radial damping rate (N/(m/s))	100
Wheel arm pivot coulomb friction (Nm)	50
Wheel arm pivot viscous friction (Nm/(m/s))	250
Static road load (N/kg)	0.040
Velocity road load (N s/kg m)	0.002
Road load height (m)	0.500

Damping Characteristic – Wheel stations 1, 2 and 5 only:

Arm velocity (rad/s)	ArmTorque (Nm)
-20.00	35000
-4.00	4200
-2.25	3800
-1.50	3450
0.00	0
0.75	-1250
1.50	-3200
4.00	-4500
20.00	-30000

Data Specific to Vehicle

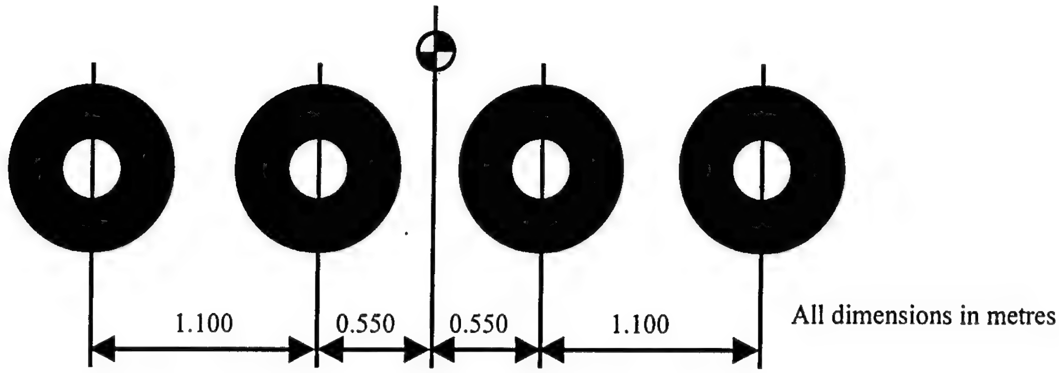
Stiffness Characteristic TR-1 and TR-2

Arm angle (rad)	Torque (Nm)
-0.500	400000
-0.332	18223
0.175	6087
0.428	0
1.000	-13726

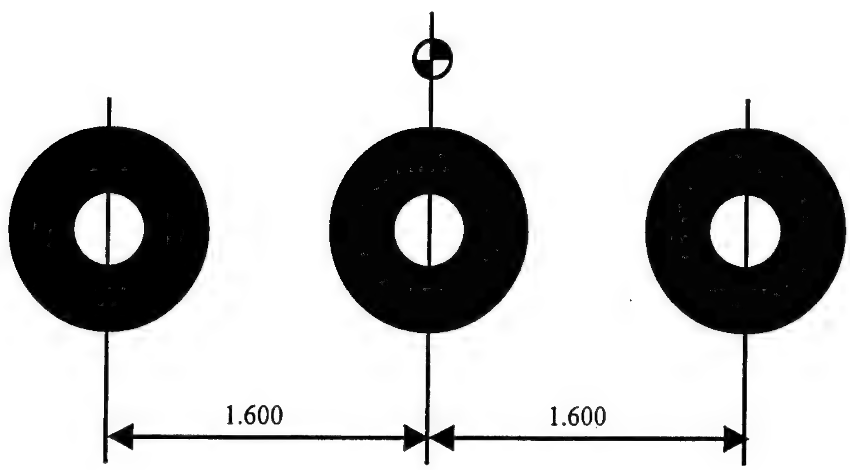
Stiffness Characteristic TR-3

Arm angle (rad)	Torque (Nm)
0.800	460000
0.673	35000
0.400	20000
0.175	6087
0.650	0
1.000	-5000

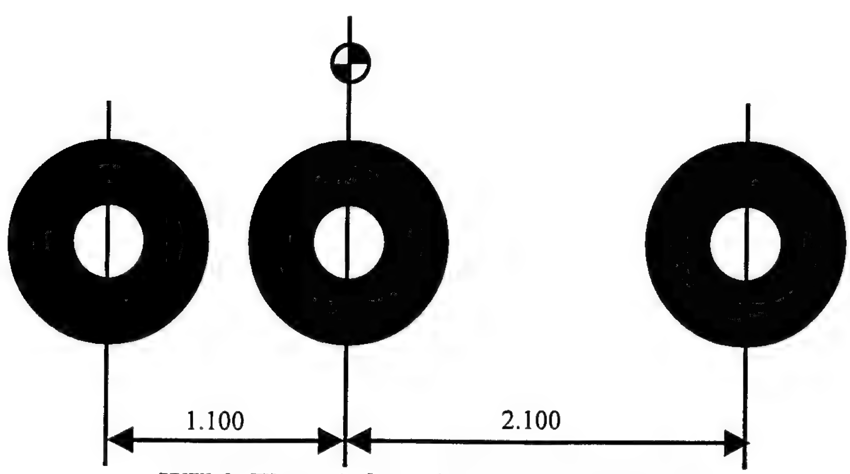
ANNEX 2B – WHEELED VEHICLE DATA



WH-1 Four Equally Spaced Axles



WH-2 Three Equally Spaced Axles



WH-3 Three Axles – Close Coupled at Rear

Figure 2B.1 – Layout and Dimensions of Wheeled Variants

Hull mass (kg)			15000
Hull pitch moment of inertia (kg m^2)			30000
Mass factor equivalent of rotating parts			1.2

		WH-1	WH-2	WH-3
Half axle mass (kg)		375	650	650
Road wheel rolling radius(m)		0.400	0.500	0.500
CG to axle (m):	Axle No			
	1	1.650	1.600	2.100
	2	0.550	0.000	0.000
	3	-0.500	-1.600	-1.100
	4	-1.650		
Tyre radial stiffness (N/m)		500000	650000	650000
Tyre radial damping rate (N/(m/s))		1000	1300	1300

Stiffness characteristic

	Wheel Disp (m)	Force (N)
WH-1 All axles	-0.250	456000
	-0.200	55900
	0.000	18400
	0.200	–19100
	0.250	-419000
WH-2 All axles	-0.250	475000
	-0.200	74500
	0.000	24500
	0.200	–31600
	0.250	-432000
WH-3 Axles 1 and 2	-0.250	469000
	-0.200	68800
	0.000	18800
	0.200	-31200
	0.250	-431000
WH-3 Axle 3	-0.250	486000
	-0.200	85900
	0.000	35900
	0.200	-14100
	0.250	-414000

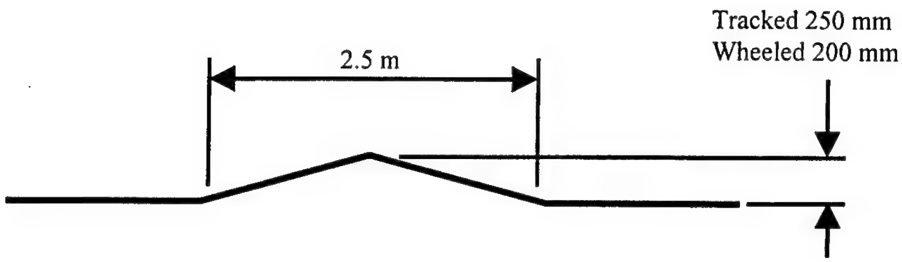
Damping characteristic

	Wheel Vel (m/s)	Force (N)
WH-1 All axles	-20	500000
	-10	100000
	-4	100000
	0	0
	4	-100000
	10	-100000
	20	-500000

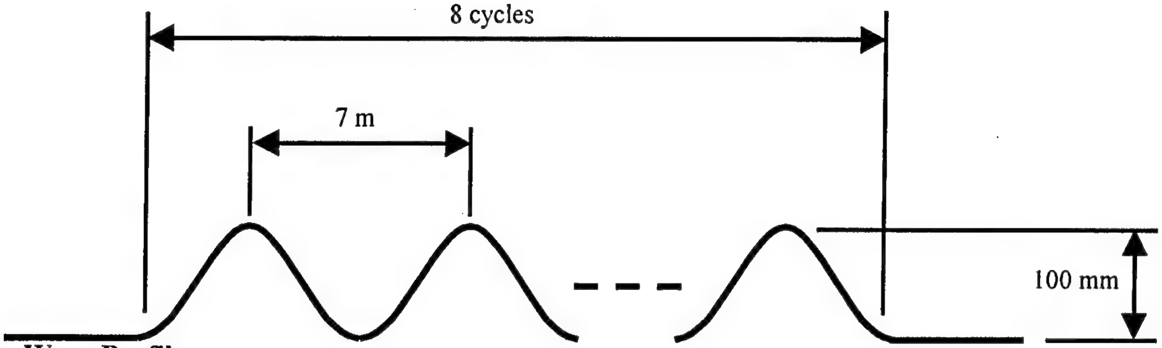
WH-2 and WH-3 All axles	Wheel Vel (m/s)	Force (N)
	-20	666000
	-10	133000
	-4	133000
	0	0
	4	-133000
	10	-133000
	20	-666000

Wheel vertical Coulomb friction (N)	100
Wheel vertical viscous friction (N/(m/s))	350
Static road load (N/kg)	0.030
Velocity road load (Ns/kg m)	0.001
Road load height (m)	0.400

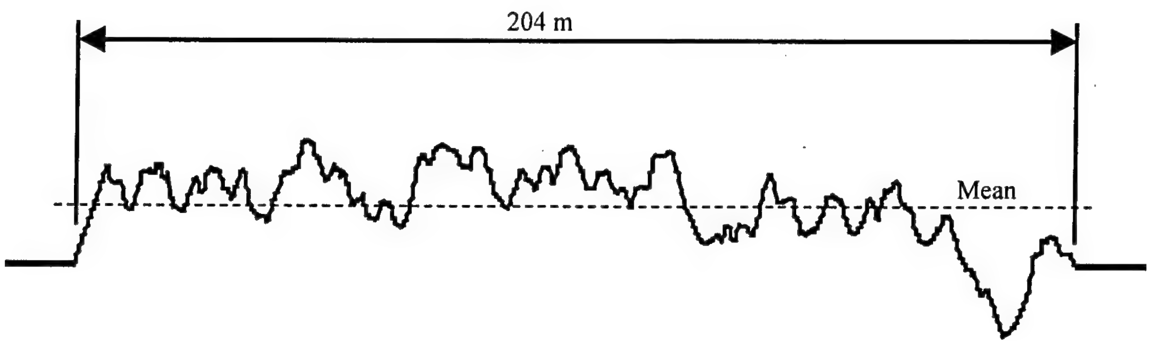
ANNEX 2C – TERRAIN PROFILE DATA



Ramp Profile



Sine Wave Profile
Horizontal interval 0.4 m



Random Profile

Horizontal interval	0.2 m
Mean height	0.428 m
rms height	0.137 m

Figure 2C.1 Terrain Profiles

ANNEX 2D – TRANSMISSION DATA

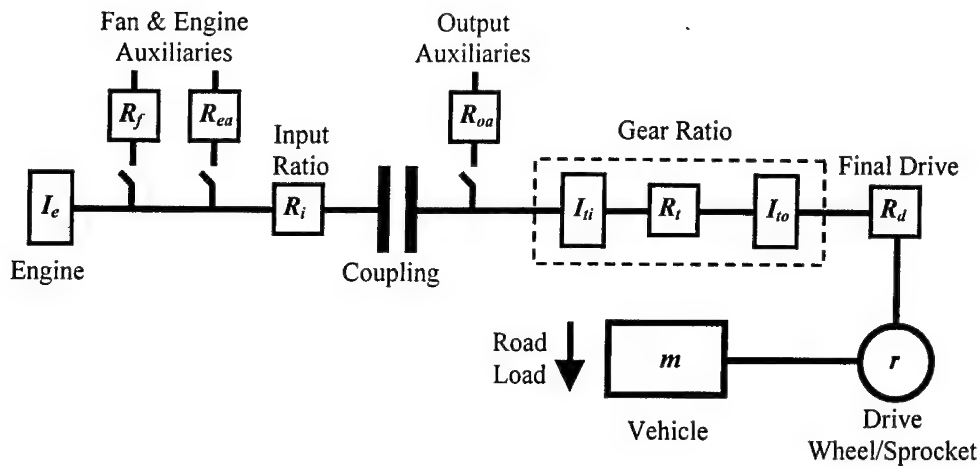


Figure 2D.1 – Schematic of Transmission System

Common Data

Vehicle mass (kg)		18000
Final drive ratio		4.5
Final drive efficiency		0.9
Sprocket/Wheel diameter (m)		0.6
Road load	Speed (m/s)	Resistance Coefficient (N^{-1})
	0	0.030
	10	0.034
	20	0.045
	30	0.065
	40	0.090
	50	0.120
Engine inertia (kg m^2) (including all components up to coupling input referred to engine speed)		2.4
Engine idle speed (rev/min)		650
Engine torque lag time constant (s)		1.5
Engine characteristic - driving	Speed (rev/min)	Torque (Nm)
	500	500
	750	720
	1000	900
	1250	1040
	1500	1190
	1750	1310
	2000	1380
	2250	1350
	2500	1260
	2750	1150

Engine characteristic - motoring	Speed (rev/min)	Torque (Nm)
	500	-130
	1500	-150
	2800	-250

Fan characteristic	Speed (rev/min)	Torque (Nm)
	0	0
	1000	6.5
	2000	20
	3000	36
	4000	59

Engine auxiliaries characteristic	Speed (rev/min)	Torque (Nm)
	0	0
	1000	2
	2000	5
	3000	9
	4000	14

Manual Change with Friction Clutch

Engine speed for up-change (rev/min)	2600
Input inertia (kg m^2)	0.7

(including all components from coupling output to gear change referred to input speed)

Gear data	Ratio	Efficiency	Output Inertia (kg m^2)
L	6.000	0.85	12.0
1	4.193	0.86	16.0
2	2.930	0.87	18.0
3	2.048	0.88	19.0
4	1.431	0.89	21.0
H	1.000	0.90	21.5

(Output inertia includes all components from gear change to vehicle referred to output speed)

Maximum friction clutch torque capacity (Nm)	4200
Minimum friction clutch engaging time (s)	1.5

Automatic Change with Torque Converter

Torque converter lock-up gears	3 and 4
Lock-up clutch capacity (Nm)	4200
Lock-up clutch engaging time (s)	0.5
Maximum allowable slip for up change	0.1

Torque converter characteristic	Speed Ratio	Torque Ratio
	0.0	2.50
	0.8	0.98
	2.0	0.98

Torque converter capacity	Speed Ratio	Capacity (Nm min/rev)^2 $\times 10^{-3}$
	0.00	0.018
	0.75	0.016
	0.92	0.009
	1.00	0.000
	1.50	-0.100

Input inertia (kg m^2) 0.7
(including all components from coupling output to gear change referred to input speed)

Gear data	Ratio	Efficiency	Output Inertia (kg m^2)
L	6.000	0.850	12.0
1	3.302	0.867	16.0
2	1.827	0.884	18.0
H	1.000	0.900	19.0

(Output inertia includes all components from gear change to vehicle referred to output speed)

Continuously Variable Transmission

Input inertia (kg m^2) 0.7
(including all components from coupling output to gear change referred to input speed)

Output inertia (kg m^2) 12
(including all components from CVT output to vehicle referred to output speed)

Efficiency 0.8

3 OTHER FACTORS INFLUENCING THE WHEELS vs TRACKS DECISION

3.1 INTRODUCTION

There has been, and continues to be, much debate on the subject of "Tracks versus Wheels" in relation to military vehicles. Much of the discussion is centred on the ability of a vehicle to negotiate soft ground but there are, of course, other factors which could influence the ultimate decision between wheels and tracks.

This section aims to:

- review the factors *other than soft ground trafficability* which should be considered to inform the decision between tracks and wheels,

- describe briefly the inherent design differences between tracked vehicles and wheeled vehicles,

- discuss the likely differences in the capabilities *other than soft ground trafficability* between tracked vehicles and wheeled vehicles.

The criteria for determining many aspects of a vehicle's design, including whether it should be tracked or wheeled, depend on several parameters including *how* the vehicle is used, *where* the vehicle is used and *for what* purpose the vehicle is used. The comments within this section are made in relation to armoured vehicles of mass ~20 US tons, but in order for these comments to be generally applicable, no assumptions are made in terms of *how*, *where* and *for what* the vehicle may be used.

Hence this section does NOT aim to:

rank in order of importance the factors likely to influence the choice between tracked vehicles and wheeled vehicles,

rank in order of importance the likely differences in the capabilities between tracked vehicles and wheeled vehicles,

determine outright whether tracks or wheels would be the preferred choice for any particular vehicle.

3.2 CAPACITY

For an armoured vehicle, be it wheeled or tracked, the need for adequate capacity (useable *internal* volume) is paramount; there would be little point in procuring a vehicle if it were unable to carry the personnel and/or equipment necessary to fulfil its intended role. But there is a need to minimise the *external* dimensions of an armoured vehicle in order to minimise the mass of armour required to protect it, to minimise its silhouette, and to stay within dimensional limits for transportation and road usage.

3.2.1 Packaging

The term "packaging efficiency" can be defined as the ratio of:

(The useable internal volume) : (The overall vehicle envelope volume)

Packaging efficiency is thus a measure of how effectively space is used. Tracked vehicles offer an inherent advantage over wheeled vehicles in terms of packaging efficiency on several counts:

Tracked Vehicle

The output from the engine/transmission (or powerpack) is transmitted over only a short distance to the two drive sprockets. This drive-line does not require any complex universal shaft joints since the transmission output shaft and the sprocket axes are fixed relative to the hull.

The powerpack normally contains the steering and braking mechanisms in the same unit as, or close-coupled to, the gearbox.

Skid steering involves no hull intrusion due to wheel articulation angles.

The road-wheels are of modest size, occupying less height than pneumatically tyred wheels for a vehicle of similar MMP. (See Figure 3-1).

Since there are no drive-shafts, braking or steering mechanisms associated with the individual road wheels, the suspension geometry is simple and the suspension system can readily be designed to be space efficient.

Wheeled Vehicle

The output from the engine/gearbox is transmitted to all road wheels, necessitating (typically) universally jointed shafts, bevel gears, cross-axle differentials and inter-axle differentials.

Steering linkages are usually provided on the front axle(s), but sometimes on all axles.

Wheel articulation angles required for a good turning circle lead to large lateral hull intrusions. (See Figure 3-3). The larger the diameter and width of wheel used (desirable for good trafficability), the worse this problem becomes.

Suspension systems are necessarily bulky for wheels which are both driven and steered.

3.2.2 Suspension Intrusion

Figure 3-1 shows a comparison between the transverse cross-sections of a basic tracked vehicle with torsion bar suspension and a basic wheeled vehicle with a live axle. The latter is the type of driveline and suspension system which might be drawn readily from volume commercial producers, and thus offers the cheapest solution for a wheeled vehicle.

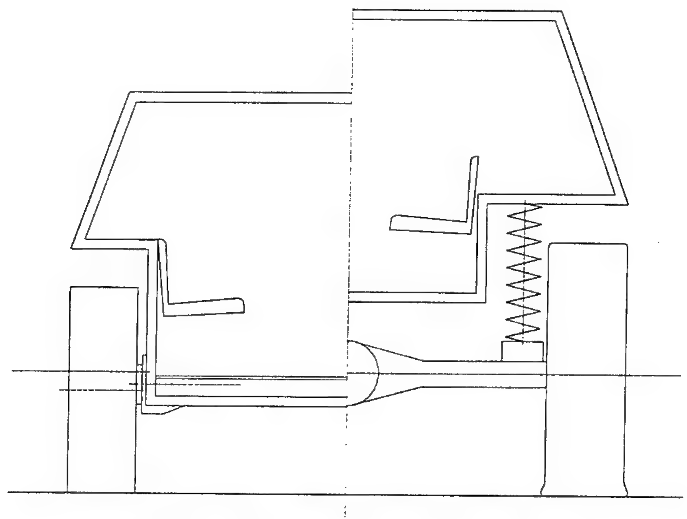


Figure 3-1 Transverse cross-section of:-
LEFT - tracked vehicle (torsion bar suspension) **RIGHT - wheeled vehicle (live axles)**

The fundamentally good packaging of the tracked vehicle cannot be improved by much even if a more sophisticated suspension were utilised instead of torsion bars. Hydrogas suspension would occupy a little less height but at the expense of useable internal width. However, Figure 3-2 illustrates how the packaging of the wheeled vehicle can be improved considerably if a more sophisticated suspension and drive-line were employed, such as H-drive with live trailing arms.

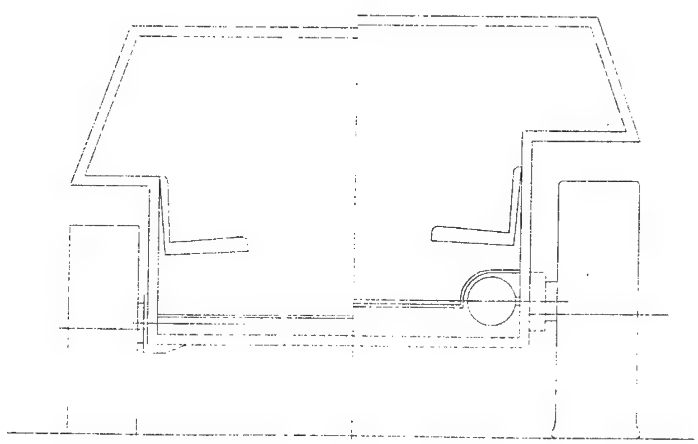


Figure 3-2 Transverse cross section of:-
LEFT - tracked vehicle (torsion bar suspension) **RIGHT - wheeled vehicle (H-drive)**

From Figure 3-2 it is apparent that there is still some penalty in terms of height and hull intrusion for the wheeled vehicle. The hull intrusion penalty is much more pronounced for the steered wheels.

3.2.3 Steering Intrusion

Figure 3-3 shows a plan view of the hull of a wheeled vehicle with Ackerman steering on the first two axles.

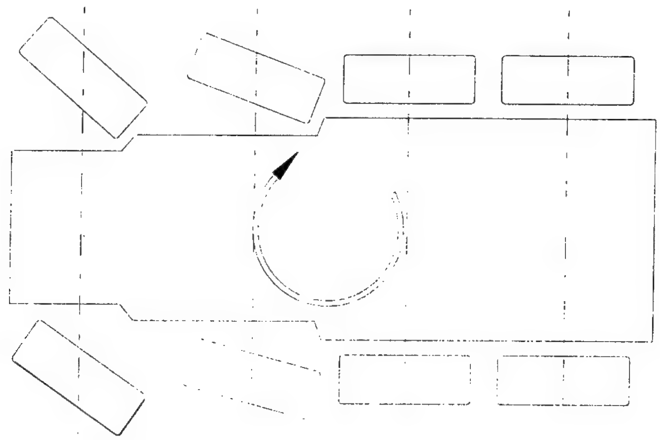


Figure 3-3 Intrusion into the Hull from the Steered Wheels

On wheeled vehicles, the steered-wheel intrusion could be eliminated by adopting skid steering such as is commonly used for tracked vehicles. Such a system would have some disadvantages such as increased tyre wear and potential high-speed handling problems. More realistically, the wheel intrusion could be reduced by using partial skid-steer, where a moderate turn radius is achieved by conventional Ackerman steer, supplemented by skid-steer only for tighter turns. Inevitably such a solution involves some increase in complexity.

3.2.4 Engine/Transmission Volume

For a given vehicle mass, a tracked vehicle requires more power than its wheeled counterpart to achieve the same level of automotive performance on roads (top speed and acceleration) due to its higher rolling resistance requiring a larger engine and gearbox. The fuel tank would also need to be larger to achieve the same road range. For an armoured vehicle with a typical maximum road speed requirement of 70 - 80 km/h, the superior packaging efficiency of a tracked vehicle would outweigh any space penalty for the engine and gearbox. However, a tracked vehicle's power requirement increases more rapidly with speed than a wheeled vehicle, so any requirement for extra automotive performance can only be met by the provision of a larger engine / powerpack with a corresponding penalty in terms of volume (and mass). However, there are reasons why very high speeds are difficult to sustain with a tracked vehicle (see Section 3.3.2). Wheeled vehicles can achieve speeds higher than 70 - 80 km/h with a comparatively low power requirement and thus a small engine / transmission.

3.2.5 Configuration

Front and rear-engined configurations are equally suited to both tracked and wheeled vehicles, so the configuration would have little influence on the decision between wheels and tracks.

3.3 MOBILITY (other than soft ground trafficability)

This section does **not** consider issues associated with soft ground trafficability. All-wheel drive is assumed for the wheeled vehicle.

3.3.1 Negotiating Obstacles

Tracks generally have the advantage when negotiating obstacles, both natural and man-made, as detailed in Section 1 and summarized below.

Tracked Vehicle	Wheeled Vehicle
Trench Crossing Tracked AFVs generally have a good trench-crossing capability. See Section 1.2.2	Trench Crossing In general, 8 x 8 AFVs have a reasonable trench-crossing capability, but three-axle, and especially two-axle vehicles, have a limited capability.
Step Climbing Tracked vehicles generally have a good step-climbing capability. See Section 1.2.1	Step Climbing Wheeled AFV's have a step-climbing capability which is generally somewhat less than their tracked counterparts.
Ground Clearance A typical ground clearance requirement of 0.45 m can be achieved without undue difficulty.	Ground Clearance A typical ground clearance requirement of 0.45 m can be achieved with independent suspension without undue difficulty, but the differential housing of a live axle is likely to foul the ground.
Static Tilt Angle Angles of 40° or more are achievable dependent upon the distance between track centres and the height of the mass centre.	Static Tilt Angle Vehicles with axles are at a disadvantage due to their high mass centre (Figure 3-1) and their low roll stiffness, and are unlikely to achieve angles of 40°. Even vehicles with a sophisticated suspension and drive-line may struggle to achieve 40° due, at least in part, to the deflection of the pneumatic tyres.
Turning Circle A neutral or pivot turn is readily achievable with modern skid steering systems.	Turning Circle Ackerman steering will permit a minimum turning circle of the order of 15 m at the expense of severe hull intrusion (Figure 3-3). With partial skid steer, as discussed in Section 3.2.3, a locked skid turn could be achieved, but not a pivot turn.

3.3.2 Automotive Performance (Speed and Acceleration)

As previously discussed, for a given vehicle mass, a tracked vehicle requires more power than its wheeled counterpart to achieve the same level of automotive performance (top speed and acceleration). As the road speed rises this difference becomes greater. However, road speeds higher than 80 km/h become impracticable for a conventional tracked vehicle, since dynamic track loadings, noise and vibration become excessive. Also, tracked vehicle handling becomes less certain at high speeds.

Wheeled vehicles have a clear advantage in terms of on-road performance; road speeds of 100+ km/h are readily achievable if required, with modest power requirements and relatively little increase in vibration and noise.

3.3.3 Off-road Performance (Ride)

In making comparisons between tracked and wheeled vehicles below, it is assumed that both have similar suspension travel and ground clearance.

The suspension performance analysis in Section 2.2 indicates that, in general, at high speed the ride is better in the tracked vehicle, but at lower speeds the ride is marginally better in the wheeled vehicle.

Over very rough ground, a tracked vehicle will generally make faster progress because its ride will be smoother. Over more moderate terrain a wheeled vehicle is likely to make faster progress unless the ground is very soft, in which case the increase in rolling resistance tends to favour tracks over wheels.

3.3.4 Legal Issues

3.3.4.1 Legal Weight Limits for Use on Public Roads

Wheeled vehicles towards the upper end of the 10 to 25 US tons range may not comply with some nation's regulations governing weight limits. Some countries do not appear to place weight restrictions on tracked vehicles.

3.3.4.2 Legal Width Limits for Use on Public Roads

The length:width ratio of tracked AFVs tends to be constrained for technical reasons (L/C ratio) which will probably result in a tracked vehicle being slightly wider than its wheeled counterpart for a given size of vehicle. Tracked vehicles at the larger end of the range being considered here may exceed the normal road-vehicle width limitations imposed by some nations. A wheeled vehicle gives the designer a *little* more flexibility in choosing the overall length:width ratio (i.e. a wheeled vehicle *could* be designed to be long and narrow) but the vehicle may still be wider than that permitted for free access to some national road networks. In trying to minimize the width of a wheeled vehicle, it may lack stability on side slopes and may suffer a larger turning circle due to the extra length necessary to maintain internal volume.

3.3.4.3 Legal Height and Length Limits for Use on Public Roads

Neither a wheeled nor tracked solution is expected to infringe height or length limits.

3.3.5 Transportability

The height difference between a wheeled and tracked solution is not likely to affect the options available for transportation by road or sea. Height limits for aircraft transportation are likely to constrain the design of the wheeled vehicle to a greater extent than a tracked vehicle. Modern railway networks are unlikely to present any height problems for either tracked or wheeled vehicles.

Similarly, most major nations' modern railway networks are unlikely to present any width problems for either tracked or wheeled vehicles. Older railway networks may not cope with the wider (i.e. generally tracked) vehicles in the range being considered. Width limitations for aircraft transportation may impinge upon the design of the tracked vehicle to a greater extent than the wheeled vehicle since the latter could be made narrow (see Section 3.3.4.2).

It is a reasonable requirement that two vehicles could be carried on a road transport trailer. This requirement could present a problem for vehicles at the larger end of the range, both tracked and wheeled, particularly so for the latter if it were made long and narrow to meet width limitations.

For long distance road movement under their own power, wheeled vehicles are more suitable because they offer better comfort at high speeds due to relatively low levels of vibration and noise. Tracked vehicles impose a cost and logistic burden in terms of fuel and tracks consumed.

3.3.6 Amphibious Capability

There are several examples of vehicles in this weight range, both wheeled and tracked, which can swim well. Wheeled vehicles tend to have superior buoyancy not least due to the tyres themselves, and, possibly, a more uniform weight distribution fore/aft. Tracked vehicles generally have fewer running-gear components needing protection against the ingress of water (for example, wheel bearings and suspension trailing arm pivots) whereas wheeled vehicles will also have drive lines and joints, steering components, suspension linkages, hub reduction gears and brake components. Some of these additional components also tend to increase the drag of the vehicle in water; a tracked vehicle has a relatively smooth underside. On the other hand the driveline of a wheeled vehicle can readily be extended to drive propeller(s) for enhanced swimming speed; tracked vehicles usually rely on the propulsive effect of the tracks alone.

Tracked vehicles are probably more able to haul themselves out of the water up a slippery bank without assistance.

3.4 SURVIVABILITY

3.4.1 Armour Carrying Capacity

Because a wheeled vehicle has an inherently poorer packaging efficiency (Section 3.2.1), the surface area requiring armour protection is greater than a tracked vehicle of a similar useable internal volume. Consequently, for the same hull mass, the armour must be thinner on the wheeled vehicle. The magnitude of this disadvantage is dependent upon the type of suspension and driveline used in the wheeled vehicle; worst is a vehicle with conventional live axles whose poor packaging efficiency leads to a large hull. A wheeled vehicle with more sophisticated suspension and driveline would be only marginally worse than its tracked counterpart.

3.4.2 Signatures

3.4.2.1 Silhouette

Because of the poorer packaging efficiency mentioned above, the silhouette of a wheeled vehicle is likely to be higher than its tracked counterpart of a similar useable internal volume. This height penalty can be significant if a suspension system incorporating live axles is employed (Section 3.2.2).

3.4.2.2 Noise

A tracked vehicle generates more noise than a wheeled vehicle, the tracks themselves being largely responsible. Also, the nature of the sound is more recognisable as being that of a military vehicle.

3.4.2.3 Thermal / Infrared

A tracked vehicle frequently generates more heat from its exhaust and cooling system than a wheeled vehicle due to its need for more motive power over most types of terrain. The tracks themselves become hot in use but they can be partly shrouded by skirts. Wheels and tyres do not normally get as hot as tracks, but they are more difficult to shroud, particularly so for steered wheels. The size and shape of hot wheels/tyres can present a distinctive thermal signature. When viewed from above, a vehicle's tyres or tracks leave a temporary thermal imprint on the ground; this effect is more marked for tracks than for tyres.

3.4.2.4 Radar

Wheels and pneumatic tyres, and the hull shaping to accommodate them, may present a more discernible radar reflection than for a tracked vehicle.

3.4.3 Agility

In the context of enhancing survivability, agility is the combination of speed/acceleration and manoeuvrability. Wheeled vehicles tend to offer better speed and acceleration, but tracked vehicles are more manoeuvrable, particularly in terms of their turning circle. Refer to Sections 3.3.1, 3.3.2.

3.4.4 Mine Blast Protection

Injuries to personnel inside a vehicle subjected to a large mine blast can arise due to the violent accelerations and, if the vehicles is lifted clear of the ground, impact from re-landing. An unrestricted underbody architecture which allows the blast to escape freely is better than structures which impede the blast. It can be argued, therefore, that wheels may offer an advantage over tracks in this respect. A wheeled vehicle with axles is better still since its floor is further above the ground and should experience lower blast pressures (Figure 3-1). Such a vehicle also offers the potential for designing the underside to be profiled like a boat hull to enhance the dissipation of a blast. However, such a design would result in a very high (and therefore visible) vehicle whose survivability would be compromised from other threats.

3.4.5 Residual Mobility After Minor Mine Damage

A tracked vehicle will be disabled, at least temporarily, if a track is broken by mine attack. A wheeled vehicle with three or more axles can, in theory at least, retain some residual mobility even if one wheel-station is blown off. It is likely however, that some action would be required by the crew to clear away debris before proceeding.

3.4.6 Mobility After Small Arms Attack

The pneumatic tyres of a wheeled vehicle can, of course, be punctured by bullets or fragments. It is difficult to provide protection for the tyres, particularly so for steered wheels. However, for modern military tyres the rate of deflation from minor damage is fairly slow, and the on-board Central Tyre Inflation System (CTIS) can help to maintain the correct working pressure. Furthermore, the frequency of ballistic impacts on the battlefield is relatively low on surfaces less than ~1 metre above ground level. A greater problem is likely for, say, peace-keeping forces in an urban environment where close range deliberate targeting by snipers can quickly damage the tyres to the extent that the mission must be aborted. Run-flat inserts in the wheels ensure residual mobility, but replacing damaged tyres results in a considerable loss of vehicle availability as well as the cost and logistic burden.

Tracked vehicle running gear is relatively invulnerable to small arms or fragment damage which could cause a loss of mobility.

3.5 FIREPOWER

Both wheeled and tracked vehicles offer a suitable platform for many types of weapon system. It is possible that the weapon and mount selected might take the total vehicle height over the limitations imposed by transport considerations (see Section 3.3.5), particularly for a wheeled vehicle which will be higher than its tracked counterpart. If it were required to fit a large gun (say up to 105 mm) to a wheeled vehicle in the 10-25 US ton range, this would influence the choice of suspension and running gear layout. For example, live axles give rise to a platform which would be high, with a low roll stiffness, and a clear space would be needed in the centre of the vehicle to house the turret basket of a direct fire weapon. However, the fitting of such a weapon system would not preclude the selection of a wheeled vehicle *per se*.

3.6 COST

3.6.1 Acquisition Cost

It might be expected that the wheeled vehicle would be the cheaper option, given the competitive nature of the commercial truck market for vehicles in the same weight range. But, as previously discussed, the wheeled vehicle will require a special-to-purpose sophisticated suspension, drive-line and steering system if it is to compete with the capabilities of a modern tracked vehicle. There would be very few commercial-off-the-shelf *assemblies* which could be utilised in a military vehicle of this size, though some use could be made of proprietary *components*. The only reliable gauge of acquisition cost is that obtained as the result of open competition, but inspection of the comparison below would support the view that a tracked vehicle is likely to be cheaper to develop and produce, that is, lower in initial acquisition cost.

Tracked Vehicle	**Wheeled Vehicle**
Engine	Engine
Will need to more powerful than that for the wheeled option for a comparable on-road performance. Probably commercially derived.	Coupled to the transmission to form the power pack. Probably commercially derived.
Change Speed Gearbox	Change-Speed Gearbox
Probably a military special, integral part of the power pack.	Could be a commercial or commercially derived unit.
Driveline	Driveline
Output from the power pack taken via the final drive (military special, one each side) to the sprockets.	All-wheel drive comprising (typically) a transfer-box, cross-axle differentials, inter-axle differentials, several universally jointed shafts, bevel gears, hub reduction gears in each wheel. Although the system would be specifically engineered for this vehicle, *some* use could be made of proprietary commercial components, others would be special. An H-drive system would probably require a greater proportion of specially designed components compared to an I-drive.
CTIS	CTIS
Not applicable.	Military special, required on all wheels.
Brakes	Brakes
Probably incorporated into the power pack.	Required on all wheels. Significant use could be made of proprietary commercial components. Braking control for a partial skid-steer system would be special.
Steering	Steering
Incorporated into the power pack.	Usually required on the first two axles of 6x6 and 8x8 AFVs. Some use could be made of proprietary commercial components. Implementation and control for a partial skid-steer system would be special.
Suspension	Suspension
Simple trailing arms with torsion bars or hydrogas springs.	May be relatively complex, particularly for the steered wheels.
Hull	Hull
Simple shape.	More complex shape (see Fig 3-3).
Equipment Fit	Equipment Fit
Assumed the same for both options.	Assumed the same for both options.

3.6.2 Operating Cost

The cost of running, maintaining and repairing a fleet of vehicles is highly dependent on the way they are used. Generally, a tracked vehicle is not expected to cover a high mileage over its life, and is designed accordingly with many mechanical components being operated at high stress levels with a corresponding reduction in life. The engine, for example, may be uprated to produce two or three times the power of the commercial unit from which it was derived. This is a reasonable philosophy given the need to maximise the space available for the payload, allied to the fact that a tracked vehicle is not suited to high-speed long-distance travel. Also, the tracks themselves have a very short life and are expensive to replace.

Wheeled vehicles have, in the past, been designed for many roles, sometimes covering relatively large distances, hence caution is required when comparing cost data collected from in-service tracked and wheeled vehicles.

Caution should also be exercised when analysing the corrective maintenance cost for tracked and wheeled vehicles, which typically indicates a two-to-one advantage for the latter. The practice of removing entirely the powerpack from a tracked vehicle, regardless of the nature of the failure, and returning it to the manufacturer for overhaul appears to be an expensive option. But by so doing, the availability of the vehicle is maximised (see Section 3.7). On a wheeled vehicle, the replacement of an individual failed item or sub-assembly is likely to be more time consuming, degrading the availability of the vehicle. The military commander would thus need a larger fleet of vehicles to achieve the same overall availability, though the maintenance cost per vehicle may be lower.

Operating costs for a fleet of military vehicles, when taken in the broadest sense, could include the cost of the provision of a road transporter fleet. In this respect the wheeled vehicles would show a clear cost advantage if they can travel relatively long distances without the need for transporters.

3.7 SUPPORTABILITY, COMPLEXITY, MAINTAINABILITY AND AVAILABILITY

3.7.1 Tracked Vehicles

A tracked vehicle consumes large quantities of fuel and lubricants. The tracks themselves have a very limited life; replacements are bulky and very heavy to transport.

Because of its simple driveline, steering, braking and suspension systems, the tracked vehicle has relatively few components. Furthermore, most of the components on a tracked vehicle are well protected from the environment. However, should a failure occur in the engine, transmission, brakes or steering, the powerpack must generally be removed entirely and substituted, the faulty one being returned to base for overhaul. This philosophy is not cheap to implement, as powerpack overhaul is a lengthy, specialist task, but this approach maximises the *intrinsic availability*[1] of the vehicle since the design ought to be such that powerpack removal and replacement can be achieved very quickly. Also, the variety of spare parts to be carried is minimised since a powerpack is essentially just one item, albeit a large one. However, the *operational availability*[2] is likely to be worse than that of a wheeled vehicle since a replacement powerpack and the resources to fit it will not usually be instantly to hand.

Routine maintenance tasks are mainly those of oil and filter renewal and frequent track tensioning,

1 Intrinsic availability includes the actual corrective repair time but excludes the logistic delay. It is calculated as though all parts, equipment and manpower are immediately to hand.

2 Operational availability includes the logistic and administrative delays in obtaining parts, equipment and manpower, as well as the actual corrective repair time.

track, sprocket, idler and roadwheel replacement, all of which can be undertaken in the field if necessary.

3.7.2 Wheeled Vehicles

A wheeled vehicle will require smaller quantities of fuel and lubricants. The tyres have a comparatively long life but replacements are bulky to transport.

A wheeled vehicle has complex driveline, steering, braking and suspension systems (see Section 3.6.1.1), some parts of which are exposed and vulnerable to battle or accidental damage. Failure of any component or sub-assembly would normally involve replacement of that item alone which, though an economical approach, can be time consuming, reducing the availability of the vehicle and tying up maintenance resources. The inventory of parts and tools required to support the vehicle can be large.

Routine maintenance tasks are mainly those of oil and filter renewal, inspection and occasional replacement of brakes, tyres, suspension joints and linkages, all of which can be undertaken in the field if necessary.

3.8 HUMAN FACTORS

Both wheeled and tracked vehicles can be equipped with heating, air-conditioning and other facilities to maintain crew operational effectiveness. As previously mentioned, wheeled vehicles offer better comfort at high road speeds due to relatively low levels of vibration and noise, but a tracked vehicle provides a better ride over very rough ground. The floor height of a tracked vehicle is likely to be lower than that of a wheeled vehicle, allowing easier entry and egress.

3.9 POLITICAL FACTORS

Even if designed to fulfil identical roles, a tracked vehicle is perceived by many as being more aggressive than a wheeled vehicle. To field an outwardly hostile vehicle may be undesirable in some sensitive situations. In other cases it may help to make a statement of serious intent.

In peace-keeping roles, tracked vehicles may not be welcomed by the local authorities because of the surface damage caused to roads, particularly when executing tight turns.

3.10 SUMMARY

This section aims to review the factors *other than soft ground trafficability* which should be considered to inform the decision between tracks and wheels, and to describe briefly the design and capability differences between tracked AFVs and wheeled AFVs.

However, this section does NOT aim to rank these factors, nor to rank in order of importance the likely differences in the capabilities between tracked vehicles and wheeled vehicles.

Table 3-1 overleaf summarises Section 3 by indicating the factors for which tracked or wheeled vehicles tend to show an advantage.

FACTORS	**ADVANTAGE:**		
	Tracks	Wheels	Equal*
Capacity - Packaging	•		
- Steering intrusion	•		
- Suspension intrusion	•		
- Engine/transmission volume		•	
- Configuration			•
Mobility - Obstacle negotiation	•		
- Automotive performance (speed and acceleration)		•	
- Legal issues - dimensions and weight			•
- Transportability			•
- Amphibious capability			•
Survivability - Armour carrying capacity	•		
- Signatures - Silhouette	•		
- Signatures - Noise		•	
- Signatures - Thermal/Infrared			•?
- Signatures - Radar	•?		
- Agility			•
- Mine blast protection		•	
- Residual mobility after minor mine damage		•	
- Mobility after small arms attack	•		
Firepower			•
Cost - Acquisition cost	•		
- Operating cost		•	
Supportability		•	
Complexity	•		
Maintainability			•
Availability		•	
Human Factors			•
Political Factors			•

* "Equal" implies similar capabilities, or a combination of pros and cons for both wheeled and tracked vehicles

Table 3-1 Summary Table

4 MAIN CONCLUSIONS

The following conclusions are drawn from this study for AFVs in the 10-25 US ton range.

On soft clay soils, tracked AFVs have a significant trafficability advantage over wheeled AFVs. Whilst CTIS can markedly improve the trafficability of wheeled vehicles, the evidence suggests that, compared on a weight-for-weight basis, tracked AFVs still offer superior trafficability. On coarse grained soils (sands), the results indicate unequivocally that tracked AFVs have superior trafficability compared to that of wheeled AFVs even when equipped with CTIS.

Tracked AFVs are generally better able to cross undeformable trenches and climb rigid steps. It would be reasonable to expect tracked AFVs to offer a superior capability over other obstacles including those likely to be encountered in an urban environment.

Despite differences in detail, wheeled and tracked AFVs have been shown to offer similar overall rough-terrain ride characteristics. However, it is recognised that wheeled AFVs are less susceptible to high frequency vibration and noise which, in tracked AFVs, emanate predominately from the track links.

Both a hardening spring characteristic, and ample suspension travel, have been shown to be helpful in improving ride quality. The suspension travel in wheeled vehicles may have to be limited due to constraints imposed by drive line articulation.

Continuously variable transmissions are likely to give a superior automotive performance when compared with stepped-ratio transmissions, and make fewer demands on the driver.

For operation on roads, wheeled AFVs offer higher speeds and better high-speed handling, greater crew comfort and better fuel consumption.

The driveline, steering and braking systems of tracked vehicles are less complex than those of multi-axle all-wheel drive wheeled vehicles. However, the operational availability is likely to be better for wheeled vehicles.

Tracked vehicles offer better packaging than wheeled vehicles, hence tracks are considered the better option for AFVs which require a low silhouette for a given weight.

For a given internal volume and level of trafficability , tracked AFVs can carry thicker armour than wheeled AFVs. For other aspects which contribute to survivability, both tracks and wheels have strengths and weaknesses, neither offering a clear overall advantage.

For AFVs of similar capability, undertaking similar operations, tracked AFVs are likely to have lower acquisition costs but higher operating costs than wheeled AFVs. Furthermore, the lower dependency on road transporters gives a clear operating cost advantage to wheeled vehicles.